RE: Additional Information requested
Damonica.Pierson
to:
Michele Dermer
06/29/2010 02:47 PM
Cc:
David Albright, George Robin
Show Details

Follow Up:
Normal Priority.

History: This message has been replied to and forwarded.

Michele, we (C6) have used the terms 'mini-frac' and 'mini-injectivity' interchangeably, which breeds a bit of confusion. We do plan on conducting a mini-frac injection test that will involve fracturing. The description of the mini-frac injectivity test is the same as what is described in the mini-injectivity excerpt that you included in the email below. I have attached a red-line version of this attachment that changes the name of the test to mini-frac injectivity. Other references to this test will need to be updated in the permit as well. Please also take a look at the mini-frac testing protocol described in the following link from EPA Region 5. My apologies if you have already seen this, but our subsurface team would like to point out that the test description here is the same as what we are proposing.

http://www.epa.gov/r5water/uic/r5guid/r5_06dr.htm

-----Original Message-----
From: Dermer.Michele@epamail.epa.gov [mailto:Dermer.Michele@epamail.epa.gov]
Sent: Thursday, June 24, 2010 2:49 PM
To: Pierson, Damonica M SEPCO-UAS/E/C
Cc: Albright.David@epamail.epa.gov; Robin.George@epamail.epa.gov
Subject: Additional Information requested

Hi DaMonica,

We are continuing to review C6's proposal for the mini injectivity test. There seems to be a possible discrepancy when we compare the write up recently submitted (word file attached) and the information contained in Attachment I of your permit application (.pdf file attached).

The application contemplates a mini-frac **and** a mini injectivity test - with fracturing the formation a part of the mini-frac test only. The mini injectivity test write up in Attachment I of the application does not include fracturing, however the recent write up provided for the mini injectivity test **does** indicate that fracturing is a part of this test. Further, the technical literature provided to us describes mini-frac tests.

We would appreciate receiving some clarification from you on this proposed test - can you please provide EPA with a written description of the test that is being contemplated to include the stated purpose and a clear explanation of the test procedure. We do not need the step by step details, but clarification of the purpose/justification; the need to fracture, clarification of low rate and low pressure vs. high rate and high pressure, and so forth, would be very helpful.

Sincerely,

Michele

Rec'd. 6/25/10

ADMINISTRATIVE DRAFT:

POTENTIAL FOR INDUCED SEISMICITY RELATED TO THE NORTHERN CALIFORNIA CO_2 REDUCTION PROJECT PILOT TEST, SOLANO COUNTY, CALIFORNIA

Larry Myer[1], Laura Chiaramonte[2], Thomas M. Daley[1], Daniel Wilson[3], William Foxall[2], and John Henry Beyer[1]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[2] Lawrence Livermore National Laboratory, Livermore, CA
[3] Daniel Wilson & Associates, Houston, TX

June 15, 2010

LBNL Report # TBD*

LLNL Report # TBD*

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* To be determined

ADMINISTRATIVE DRAFT: POTENTIAL FOR INDUCED SEISMICITY RELATED TO THE NORTHERN CALIFORNIA CO_2 REDUCTION PROJECT PILOT TEST, SOLANO COUNTY, CALIFORNIA

Larry Myer[1], Laura Chiaramonte[2], Thomas M. Daley[1], Daniel Wilson[3], William Foxall[2], and John Henry Beyer[1*]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[2] Lawrence Livermore National Laboratory, Livermore, CA
[3] Daniel Wilson & Associates, Houston, TX

June 15, 2010

Executive Summary

The objective of this technical report is to analyze the potential for induced seismicity due to a proposed small-scale CO_2 injection project in the Montezuma Hills. We reviewed currently available public information, including 32 years of recorded seismic events, locations of mapped faults, and estimates of the stress state of the region. We also reviewed proprietary geological information acquired by Shell, including seismic reflection imaging in the area, and found that the data and interpretations used by Shell are appropriate and satisfactory for the purpose of this report.

The closest known fault to the proposed injection site is the Kirby Hills Fault. It appears to be active, and microearthquakes as large as magnitude 3.7 have been associated with the fault near the site over the past 32 years. Most of these small events occurred 9-17 miles (15-28 km) below the surface, which is deep for this part of California. However, the geographic locations of the many events in the standard seismicity catalog for the area are subject to considerable uncertainty because of the lack of nearby seismic stations; so attributing the recorded earthquakes to motion along any specific fault is also uncertain. Nonetheless, the Kirby Hills Fault is the closest to the proposed injection site and is therefore our primary consideration for evaluating the potential seismic impacts, if any, from injection. Our planned installation of seismic monitoring stations near the site will greatly improve earthquake location accuracy.

Shell seismic data also indicate two unnamed faults more than 3 miles east of the project site. These faults do not reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 m). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago, which indicates that these faults are not currently active. Farther east are the Rio Vista Fault and Midland Fault at distances of about 6 miles (10 km) and 10 miles (16 km), respectively. These faults have been identified as active during the Quaternary (last 1.6 million years), but without evidence of displacement during the Holocene (the last 11,700 years).

* Short biographies of authors are provided in Appendix 1.

The stress state (both magnitude and direction) in the region is an important parameter in assessing earthquake potential. Although the available information regarding the stress state is limited in the area surrounding the injection well, the azimuth of the mean maximum horizontal stress is estimated at 41° and it is consistent with strike-slip faulting on the Kirby Hills Fault, unnamed fault segments to the south, and the Rio Vista Fault. However, there are large variations (uncertainty) in stress estimates, leading to low confidence in these conclusions regarding which fault segments are optimally oriented for potential slip induced by pressure changes. Uncertainty in the stress state can be substantially reduced by measurements planned when wells are drilled at the site.

Injection of CO_2 at about two miles depth will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly. Pressure changes have been predicted quantitatively by numerical simulation models of the injection. Based on these models, the pressure increase on the Kirby Hills Fault at its closest approach to the well due to the injection of 6,000 metric tons of CO_2 would be a few pounds per square inch (psi), which is a tiny fraction of the natural pressure of approximately 5,000 psi at that depth. The likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded earthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards any appreciable distance.

Therefore, in response to the specific question of the likelihood of the CO_2 injection causing a magnitude 3.0 (or larger) event, this preliminary analysis suggests that no such induced or triggered events would be expected. However, it is possible that a fault, too small to be detected by the existing seismic data, yet sufficiently large to cause a magnitude 3 event, could exist in close proximity to the injection point where the pressure increase could cause slippage. However, the existence of such a fault would be detectable in the data planned for collection from the well prior to injection. We do note that natural earthquake events of up to 3.7 in magnitude have occurred in this area and would be expected to occur again regardless of the proposed CO_2 injection.

To reduce the uncertainties discussed above, we recommend (1) installing a seismic monitoring network to record natural and possible induced seismic activity before, during, and after CO_2 injection; (2) collecting well log data and core samples from the wells to assess the in-situ stress state and fracturing near the wells; (3) using this information to refine operating procedures to minimize the risk of significant induced seismicity and develop a protocol for mitigation should it occur; (4) conducting geomechanical analyses and developing a probabilistic seismic hazard analysis (PSHA) during and after injection; (5) as the project progresses, relocating microearthquakes in the Northern California Seismic Network catalog, calculating focal mechanisms where possible, and improving characterization of the Kirby Hills Fault; and (6) evaluating PSHA results for the Montezuma Hills area.

Introduction

The objective of this report is to analyze the potential for induced seismicity due to a proposed small-scale CO_2 injection project in the Montezuma Hills.

To address this question, it is necessary to understand the present-day stress state, its relationship with the preexisting faults in the area, and the effects of pressure changes resulting from injection activities. Therefore, currently available information on faults and the stress state in this region has been assembled and used in conjunction with preliminary simulation data to assess the potential for slip on the preexisting faults. Finally, recommendations are made for specific actions to address the potential for induced seismicity due to injection operations.

Faults in the Vicinity of the Montezuma Hills

Figure 1 shows mapped faults in the vicinity of the proposed small-scale injection project. Information is reproduced from the California fault map compiled by the California Geological Survey (CGS) (Jennings and Bryant, 2010; http://www.consrv.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx), which is the state agency responsible for assessing the natural seismic hazard potential throughout California. Also shown are a small subsurface fault, the Sherman Island Fault, and the blind Midland fault, both identified in a report on the probabilistic seismic hazard analysis (PSHA) supporting the California Department of Water Resources Delta Risk Management Strategy (DRMS) (URS Corporation/Jack R. Benjamin & Associates, 2007).

Kirby Hills Fault

The trace of the Kirby Hills Fault (KHF) on the CGS fault map is located approximately 3 miles (5 km) west of the proposed injection site (Figure 1). The CGS map characterizes the KHF as active during the Quaternary (last 1.6 million years), but finds no evidence of surface displacement along the fault trace since the early Quaternary period (at least 700,000 years ago) (Jennings and Bryant, 2010). (The Vaca fault immediately to the north is shown as active during the last 700,000 years.) However, based on seismic reflection data along the Sacramento River and on microseismicity, Parsons et al. (2002) concluded that the KHF zone has been recently active at depth, predominantly in a strike-slip (SS) direction, and along a fault plane that dips 80°–85° east. The DRMS report characterizes the KHF as active in the Holocene (last 11,700 years). Figure 2 shows the earthquakes recorded by the USGS/UC Berkeley Northern California Seismic Network (NCSN) between 1974 and 2001, relocated by Parsons et al. and assumed to be associated with the KHF zone. Microearthquake focal mechanisms presented by Parsons et al. (2002) reveal both strike-slip and reverse components of fault slip, with the reverse component increasing to the north of the proposed injection well location. The majority of the earthquake hypocenters located by Parsons et al. lie between 9 and 17 miles (15 and 28 km) in depth, which is unusually deep for this region of California.

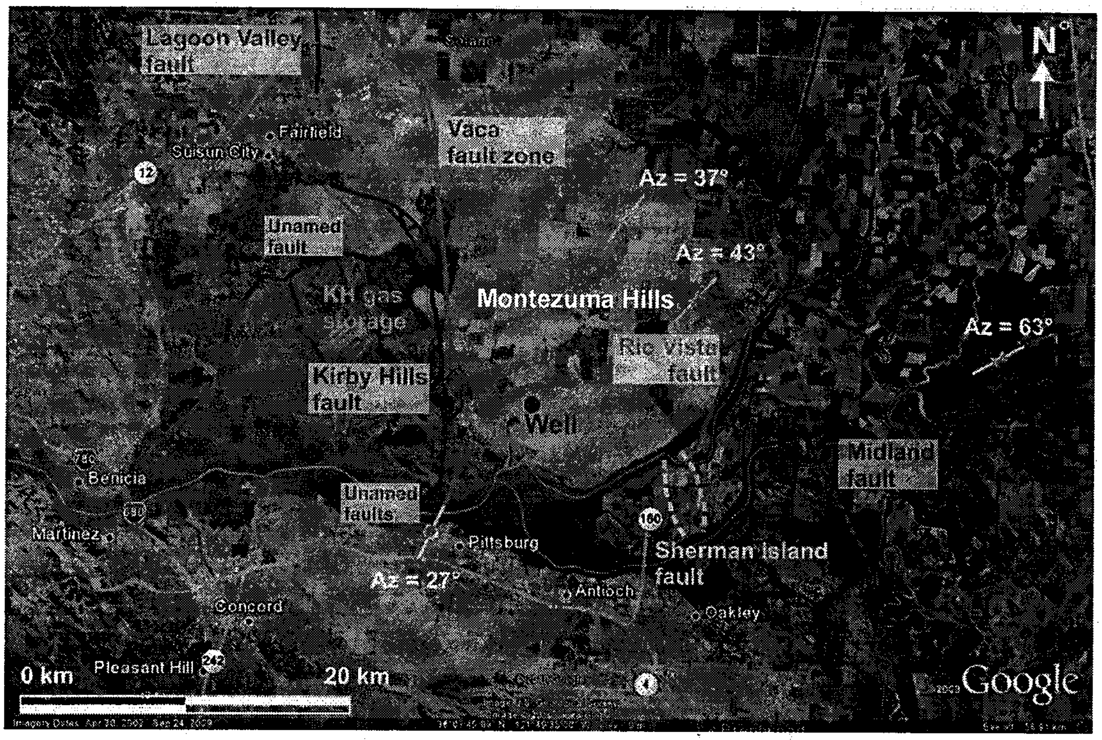

Figure 1 Faults and maximum horizontal stress (S_{Hmax}) direction in the area under study. Solid lines correspond to faults with surface expression taken from the CGS fault map (Jennings and Bryant, 2010); dashed lines are subsurface faults from the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007). S_{Hmax} directions are plotted as short gray lines (Heidbach et al., 2008). S_{Hmax} symbols with a green dot are determined from single earthquake focal mechanisms (FMS). The lines without a green dot come from borehole breakout observations. The proposed injection site is indicated with a red dot labeled "Well."

Midland Fault

The Midland Fault (Figure 1) is located about 10 miles (16 km) east of the proposed injection site. It is described in the DRMS report as an approximately 37-mile (60-km) long, north-striking and west-dipping blind fault underlying the central Delta region. It is interpreted as an early Tertiary, normal fault that was reactivated in the late Cenozoic as a reverse fault, and it is shown on the CGS fault map as active during the Quaternary, but without evidence of Holocene movement (last 11,700 years). The Midland fault has been characterized primarily from natural gas exploration well data and analysis of overlying folding. The fault breaks into a series of northwest-striking splays associated with a series of active and abandoned gas fields in the Sacramento Valley between the towns of Rio Vista and Woodland (URS Corporation/ Jack R. Benjamin& Associates, 2007).

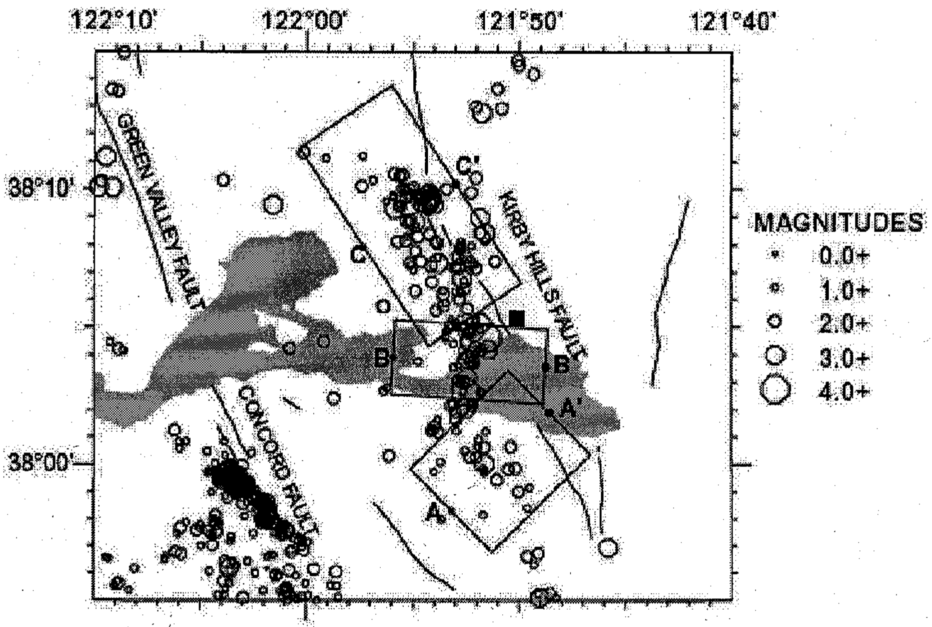

Figure 2: Kirby Hills Fault zone and associated seismicity from 1974–2001, recorded by the Northern California Seismic Network and relocated by Parsons et al. (2002). The proposed well site is shown by a green square.

Sherman Island/Rio Vista Fault Zone

The Sherman Island fault zone, at its closest point, is located approximately 5 miles (8 km) southeast of the proposed injection site (Figure 1). According to the DRMS report, this fault has been identified only in the subsurface and was active in late Cretaceous-early Tertiary time. To date, the fault has not been studied for evidence of Quaternary reactivation. The CGS fault map shows the Rio Vista fault at the same location as the Sherman Island fault, but the Rio Vista fault appears to have a different strike than that of the Sherman Island fault. CGS identifies the Rio Vista fault as active during the Quaternary, but without evidence of Holocene movement (last 11,700 years).

Montezuma Hills Fault

A geomorphic feature trending NNW-SSE along the southwestern edge of the Montezuma Hills is identified as the "Montezuma Hills Fault" in a California Division of Mines and Geology (DMG) report (1983). However, DMG Fault Evaluation Report FER-136 (1982) cites evidence from geophysical surveys, boreholes, and trench excavations that the feature is likely erosional, resulting from a meander of the Sacramento River. As a result of this evidence, William A. Bryant, a lead author of both reports, said that the feature is not shown on subsequent CGS fault maps. Upon seeing the seismic profile shown in Figure 4 below, Bryant said that this corroborates the interpretation that the Montezuma Hills "Fault" is, in fact, an erosional feature (Bryant, 2010).

Unnamed Buried Faults

As discussed in the Seismic Data Interpretation section below, two faults were detected at least 3 miles east of the project area by Shell's east-west trending 2D seismic line. They are not shown on geologic maps because they do not reach the surface.

Natural Seismicity in the Project Area

The microearthquakes relocated by Parsons et al. (2002) and assumed to be associated with the KHF zone (Figure 2) were discussed above. Figure 3 shows the NCSN catalog locations of magnitude 2.5 and greater earthquakes within the area immediately surrounding the project site for the period January 1, 1978, through January 28, 2010. The largest event recorded within the area during this period has a catalog magnitude of 3.7 and depth of 22 km (14 miles). Preliminary examination of the recorded NCSN data indicates that the uncertainties in many of the catalog locations may be relatively large, due primarily to the scarcity of recording stations in the surrounding area, particularly to the east of the injection site (Figure 3). Therefore, a focused study of the locations and mechanisms of the better recorded events should be carried out to better define the relationship of the microearthquakes to the KHF in the immediate vicinity of the site. The largest earthquake recorded in the larger area considered by Parsons et al. (Figure 2) was M 4.3. This event was located at a depth of 20 km (12 miles) below the confluence of the San Joaquin and Sacramento Rivers.

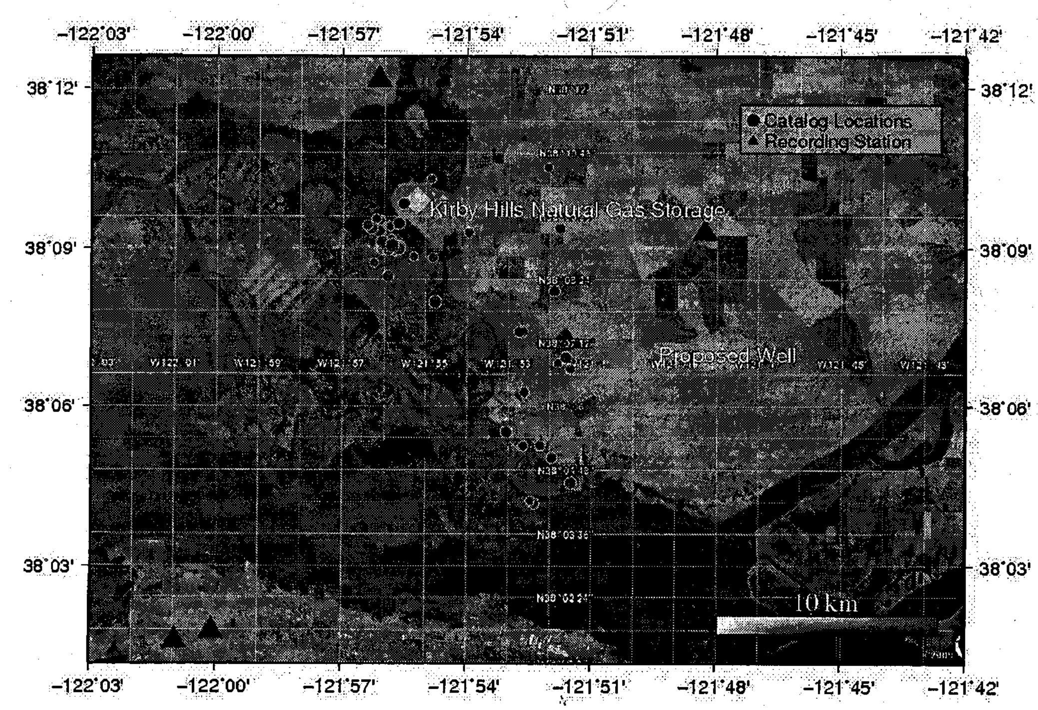

Figure 3. Seismicity with magnitude of at least 2.5 for the period 1/1/78-1/28/10 (red dots) in the area surrounding the injection site (green square) from the NCSN catalog. The largest event had a magnitude of 3.7. Blue triangles are NCSN recording stations.

Seismic Data Interpretation

Shell developed an initial model of the subsurface geologic structure in the vicinity of the project based in part on an internal interpretation of twenty 2D seismic lines. LBNL has carried out an independent analysis of the seismic data and concurs with the Shell interpretation. As shown in Figure 4, the seismic data indicate that the structures closest to the proposed injection well are two unnamed faults (labeled Fault A and Fault B), and the Kirby Hills Fault.

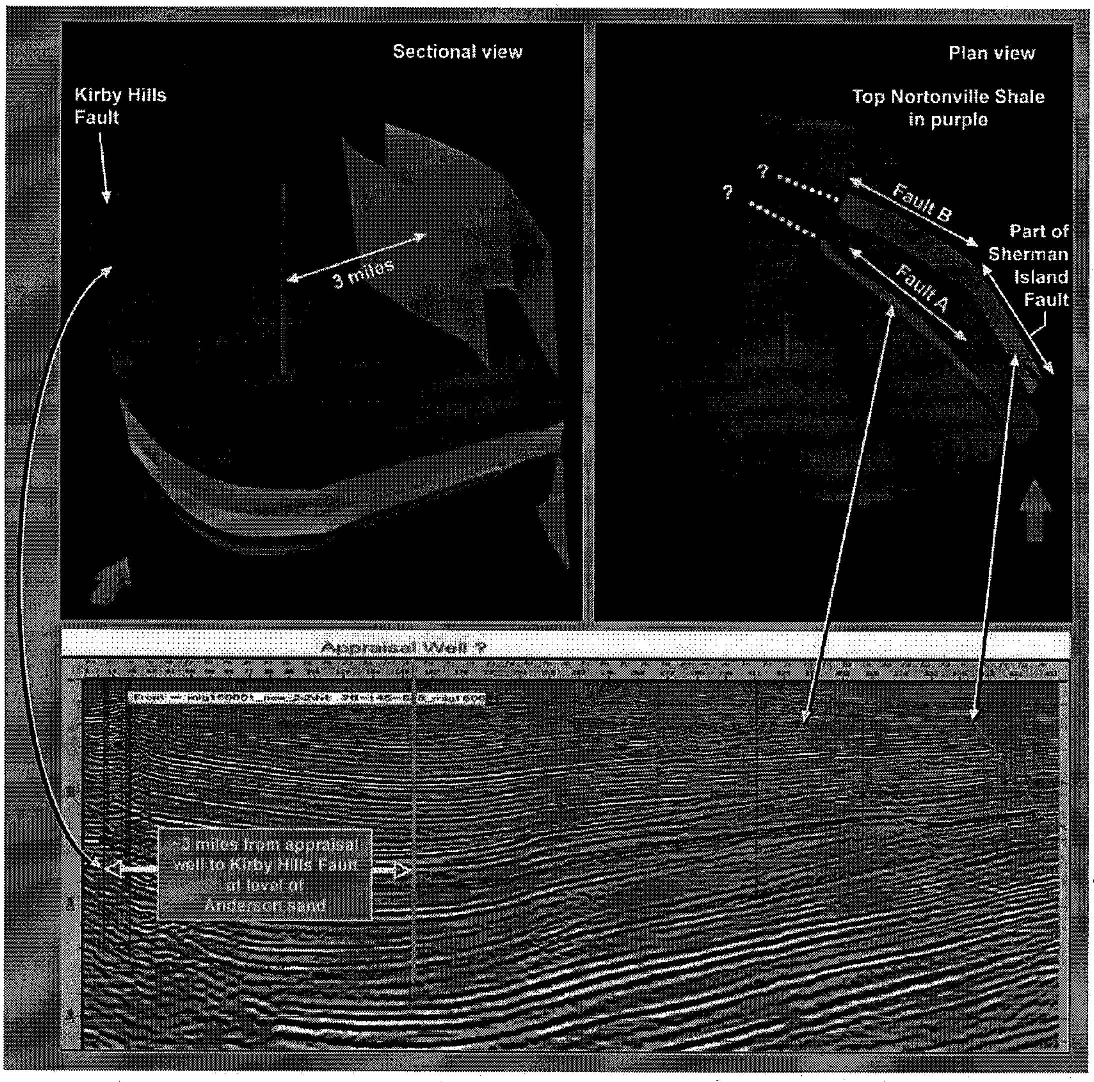

Figure 4: *Top*: Views of Shell's 3-D geologic model based on offset well log data and twenty 2-D seismic lines showing the Kirby Hills Fault, buried Fault A and Fault B, and site of proposed well. *Bottom*: Shell's east-west 2D seismic line, which passes about 1,700 feet (520 m) south of the proposed well location, showing interpreted Kirby Hills Fault Zone and buried Faults A and B. This model and all the seismic data were reviewed by Daniel Wilson, one of the report authors; he concurs with Shell's analysis and interpretation of the data.

Fault A is more than 3 miles (5 km) from the proposed injection well at reservoir depth. Neither Fault A nor Fault B reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 m). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago. Since the faults do not extend into the formations overlying the unconformity, it indicates that these faults have not been active since the Oligocene. Both faults trend toward the Sherman Island fault, but further work is required to evaluate their possible relationship to the Sherman Island Fault. The seismic data also show that the Kirby Hills Fault is about 3 miles (5 km) from the proposed injection well at reservoir depth. The primary indicator of the Kirby Hills Fault in the seismic data is a "wash-out" of the seismic signals (similar to the expression of the fault in the seismic data along the Sacramento River presented by Parsons et al. [2002]). Improved delineation would require acquisition of additional seismic data.

Stress State

Limited information on the present day stress state was found for this area. Orientations of the maximum horizontal stress were compiled from the World Stress Map (Heidbach et al., 2008). The mean maximum horizontal stress (S_{Hmax}) azimuth is 41°. Measured values (Figure 1) near the proposed pilot well are 20°, 27°, 37°, 43°, 54° and 63°. These orientations were estimated from single focal mechanisms (FMS) (short gray lines with green dot in Figure 1) and borehole breakouts (short gray lines). The FMS analyses also indicated a strike slip (SS) stress regime.

Dr. Haibin Xu from Shell performed a Fracture Pressure Prediction study and found indications from leak-off tests and seismic observations of offsets on the faults that the stress state could accommodate reverse faulting (RF regime) at the surface and strike slip (SS regime) at depth (Xu, 2010). The limited available information regarding the stress state indicates that the area surrounding the injection well could be an oblique faulting SS/RF environment, consistent with the focal mechanism solutions reported by Parsons et al. (2002). Uncertainty in the stress state can be substantially reduced by measurements made when the proposed well is drilled.

Relationship Between Faults and *In situ* Stress

Knowledge of the orientation of the *in situ* stresses enables identification of faults that are most prone to movement under that stress regime. This is the first step in evaluating the likelihood of fault movement, which also requires an analysis of the magnitude of stress change required to cause movement on a fault. Under a strike slip (SS) stress state, faults oriented approximately ±30° from the S_{Hmax} direction are most prone to slip. Under a reverse faulting (RF) environment, the optimal fault orientation for movement is sub-perpendicular to the S_{Hmax} direction (Zoback, 2007). However, there are certain values of the *in situ* stress tensor that correspond to both SS and RF regimes. If a region is characterized by an SS/RF state of stress, then faults having multiple orientations could be prone to movement at the same time.

Figure 5 shows the faults and stress orientation near the proposed injection well based on currently available data. It also shows the mean S_{Hmax} direction (red line in lower right circle), the optimal direction for movement in a SS regime (dotted green lines), and the optimal direction for movement in a RF regime (blue line).

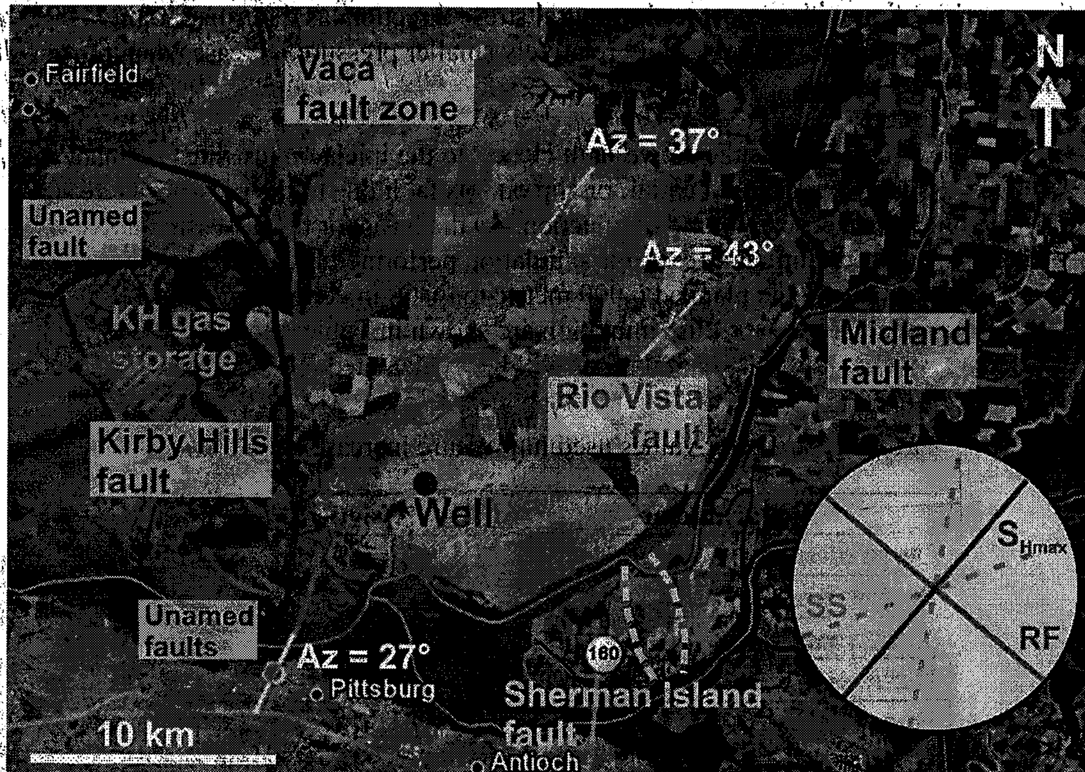

Figure 5: Faults and maximum horizontal stress direction near the proposed injection well (red dot). The circle in the lower right corner shows the mean S_{Hmax} direction (red), the optimal directions for fault movement for SS (green) and for RF (blue).

Comparison of the SS and RF directions with the fault traces shown in Figure 5 suggests that segments of the KHF, the unnamed faults south of the KHF, and the Rio Vista Fault, are oriented in directions most favorable for movement. The level of confidence in this conclusion is low, however, due to the large scatter in the stress observations near the injection well, which results in uncertainty in the orientation of the stress field, and due to uncertainty in the geometry of the fault planes at depth. Since the KHF is active, it is assumed that its fault plane is favorably oriented for slip at least in the depth range within which microearthquakes have occurred. It is possible that the *in situ* stress orientations change with depth, but additional data are required to support such a hypothesis.

Relationship Between Faults and Reservoir Pressures

Injection of CO_2 will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly, approaching pre-injection values for situations in which the storage reservoir is very large in comparison to the volume of injected fluid. It is well known that injection operations can induce fault movement if pressures in a fault zone are increased to a level where the resistance to slip on the fault is exceeded. Faults with optimum orientations with respect to the horizontal stress direction as described in the previous section, will in general require relatively smaller pressure increases than those having other orientations.

Since the Kirby Hills Fault is the active fault closest to the injection test site, we made a preliminary assessment of the potential for slip on this fault due to the pressure increase expected from the proposed volume of injection. As the basis for this assessment, we used the results of a preliminary reservoir simulation performed by Shell to predict pressure increases due to the planned 6,000 metric ton CO_2 injection. The values for subsurface parameters used for this simulation are shown in Table 1. After the first well is drilled and data are collected, simulations will be recalculated.

Table 1. Parameter values used in pressure increase simulations

Parameter	Assigned Value
Depth of injection	11,200 feet TVDss*
Pore pressure	4,800 psi
Temperature	228°F
Net-to-Gross Ratio	1
Porosity	20%
Permeability	20 millidarcies
Vertical/horizontal permeability ratio	0.1
Dip angle	3 degrees

* True vertical depth subsea

The western boundary of this model was placed at about 10,000 feet (1.8 miles, 3 km) from the injection well in the form of a "no-flow" hydrologic boundary condition (equivalent to the assumption of a sealing fault). The simulated increase in pressure at the western boundary of the model is less than 0.08 MPa (12 psi), which corresponds to 0.2% of the hydrostatic pore pressure of about 5,000 psi (34.5 MPa) at the Anderson Formation depth of 2.1 miles (3.4 km). This maximum pressure increase occurred 150 days after injection stopped, with pressure declining thereafter. The Kirby Hills Fault is about 1.2 miles (2 km) farther to the west from the western boundary of the model and so the pressure increase extrapolated from the model to the fault at a depth of about 2.1 miles (3.4 km) would be considerably less than 12 psi. Even if the fault is optimally oriented for movement at the injection depth, the likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded micro-earthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards over any appreciable distance (e.g., Segall, 1989).

Discussion

To understand what size of fault can produce a magnitude 3 earthquake, we can use one of the numerous scaling relationships for the magnitude of an earthquake versus the area of slip (e.g., Shaw, 2009; Kanamori, 1977). Using Kanamori (1977), a 250-m (820-ft) radius fault is needed to produce a magnitude 3 earthquake, which would correspond to a circular fault area of ~0.2 km^2 (~0.08 mi^2). This could easily be accommodated by any of the faults discussed above. However, as discussed in previous sections, multiple factors influence the potential for slip on any particular fault. Based on Shell's preliminary reservoir modeling, the faults near the injection well would experience, at most, a very small increase in fluid pressure. Therefore, this preliminary analysis suggests that no slip events would be expected due to the proposed injection.

In general, the greatest increase in storage reservoir fluid pressure occurs in a limited volume around the injection well; for example, Shell's reservoir simulations showed that the region of pressure increase in excess of 30 psi (0.21 MPa) will extend for about 0.6 mile (1 km) in all lateral directions from the well. Review of the seismic reflection data did not reveal any faults within this area. However, if a fault or fracture with a radius of 820 feet (250 m) does exist this close to the CO_2 injection point, the resolution of the existing seismic data is probably not sufficient to detect it. Therefore, based on currently available data, it is not possible to say whether or not a fault or fracture of 250-m radius is present near the proposed well. However, a stress increase of even 30 psi is relatively insignificant compared to the estimated natural pressure of about 5,000 psi at the injection depth, so the likelihood of triggering an event is also relatively small. Once the well is drilled, information will be available to reduce this uncertainty significantly.

As discussed above, the injection operation is not expected to cause slip on the Kirby Hills Fault. However, review of the natural seismicity reveals several naturally occurring earthquakes having magnitudes greater than 3 since the late 1970s. A recurrence analysis has not yet been carried out, but a natural earthquake greater than magnitude 3 will certainly occur eventually in the area, independent of any possible effects of the injection project.

If future injection projects involving larger volumes are considered for this site, a site-specific probabilistic seismic hazard analysis (PSHA) is recommended. PSHA is the calculation of the probability that a particular ground-motion measure (acceleration or velocity) will exceed given amplitude thresholds at one or more places of interest during a specified time period (e.g., Hanks and Cornell, 2008). The first step would be to refine the PSHA for the naturally-occurring seismicity in the area published by CGS/USGS by carrying out more detailed characterization of the local active faults. The second step would be to assess the influence on the seismic hazard of potential induced seismicity associated with a large-scale injection project.

At present, definitive, quantitative statements about the likelihood of induced seismicity are difficult to make because of the present lack of data and uncertainty in the subsurface structure. To improve risk assessment and to begin acquiring the data necessary for analysis, a high-resolution microseismic monitoring network should be installed to detect and locate seismic events that might occur in the site region. This local network would be capable of detecting smaller events than the USGS regional network and provide improved event location accuracy. The network should be integrated into the regional seismic network and installed as soon as possible, in order to record the maximum number of naturally occurring events as a baseline before injection of CO_2 begins.

Conclusions and Recommendations

Initial geologic characterization studies performed to date have identified mapped and unmapped faults and other structural features in the area surrounding the proposed injection well. From an analysis of the available data on *in situ* stresses and preliminary reservoir simulations, the likelihood of slip on these faults resulting from the proposed 6,000 metric ton injection is judged to be very low. Examination of the local seismicity shows that natural earthquakes having magnitudes greater than 3 have occurred in the past and consequently are likely to recur in the area regardless of injection operations.

To reduce the uncertainties discussed above (including uncertainties about fault locations and *in situ* stress directions), we recommend several actions:

1. Prior to well drilling and injection: Install a microseismic network as soon as possible to begin to compile a high-resolution baseline of natural seismicity and seismicity induced by human activities in the area. The network will remain in place to monitor for natural seismicity and any induced seismicity that may occur during injection operations.†
2. Once wells are drilled: Collect information on the *in situ* stress state and natural faulting or fracturing near the wells.
3. After drilling and prior to injection: Reassess the potential for operating conditions during injection to induce significant seismicity and develop a protocol for responding to any significant natural or induced events recorded by the network.
4. During and after injection: Carry out additional geomechanical analyses using information obtained during the small scale injection, and develop a PSHA which includes potential induced seismicity at the site.
5. Simultaneously with field work: Carry out focused studies to relocate the better recorded microearthquakes listed in the NCSN catalog for the site area and to calculate focal mechanism solutions for selected events. Evaluate the relationship of the relocated earthquakes to the KHF to improve characterization of the fault.
6. Simultaneously with field work: Evaluate PSHA results for the Montezuma Hills area in the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007).

County requested these be deleted

† Two temporary seismic stations have been installed to collect initial data. Additional details are provided in Appendix 2.

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Appendix 1
Biographies of Authors

Larry Myer is a retired Staff Scientist at Lawrence Berkeley National Laboratory, Earth Sciences Division (ESD), where he has conducted research in geophysics and geomechanics since 1981. He has a Ph.D. in Geological Engineering from the University of California, Berkeley. Dr. Myer's research experience spans a wide range from basic theoretical and laboratory investigations of rock properties and processes to field measurements of rock behavior and instrumentation development. Basic research activities have been directed at understanding the microprocesses associated with deformation and failure of rock, seismic wave propagation, and fluid flow in fractured porous media. A particular focus has been the mechanical, hydrologic and seismic properties of single fractures and faults with the development of new theoretical concepts accompanied by laboratory and field validation experiments. Dr. Myer has been leading research activities in geologic sequestration since 1999. He co-directed the DOE funded QEO-SEQ project, an applied R&D effort focused on monitoring and verification, and subsurface flow and transport in geologic sequestration. As part of the GEO-SEQ project, he led the development of the monitoring program for the Frio CO_2 injection pilot. The Frio pilot was the first saline formation CO_2 pilot in the United States. As Geologic Sequestration Program Head, he was responsible for programmatic leadership of the ESD geologic sequestration research program, a multidisciplinary effort focused on monitoring, risk, and reservoir performance of sequestration projects. The ESD Geologic Sequestration Program includes research conducted as part of major international sequestration projects, including Weyburn, Canada, Otway, Australia, and In Salah, Algeria. Most recently, until his retirement, Dr. Myer was Technical Director of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), which is evaluating CO_2 sequestration options and opportunities for the west coast of North America.

Laura Chiaramonte is in the Computational Geosciences Group at Lawrence Livermore National Laboratory (LLNL). She holds a Ph.D. in Geophysics from Stanford University (2008), an M.S. in Structural Geology and Geomechanics from Stanford University (2003) and a B.S. in Geological Sciences from the Universidad de Buenos Aires (1996). Prior to joining LLNL in 2010, she was a postdoctoral fellow at Lawrence Berkeley National Laboratory (LBNL). From 1997-2001, she worked for REPSOL-YPF in Argentina as a structural and reservoir geologist.

Tom Daley works as a research scientist in the Earth Sciences Division of Lawrence Berkeley National Laboratory. He has been with Berkeley Lab since 1987. He received a Bachelors degree in Geophysics from the University of California, Berkeley in 1980 and a Masters degree in Engineering Geoscience from UC Berkeley in 1987. He worked from 1980 to 1985 with Seismograph Service Corporation performing borehole seismic surveys and managing a district office in Ventura, CA. Tom's research work is focused on the acquisition and analysis of borehole seismic data from field scale experiments. Problems addressed have included continuous travel time monitoring to detect stress changes, monitoring of geologic sequestration of CO_2, characterization of fracture content and dominant fracture orientation in geothermal and oil fields, high resolution imaging of shallow surface materials, imaging fracture flow zones in contaminated aquifers, and geophysical characterization of volcanic tuff flows for nuclear waste isolation at Yucca Mountain. Tom is a member of AGU since 1987 and has been a member of SEG since 1980, and is currently on the SEG CO_2 research subcommittee.

Daniel Wilson is the principal at Daniel Wilson & Associates, Inc., a geophysical consultancy near Houston, Texas. Mr. Wilson has 40 years of experience interpreting seismic data for the evaluation and development of oil and gas prospects. From 2003-2009 he consulted for Davis Petroleum Corp. and Stephen Production Co. analyzing and reprocessing 3D seismic data for several prospects in Louisiana and Oklahoma. From 1992-2003 he worked as a Geophysical Advisor for Anadarko Petroleum interpreting 2D and 3D seismic data, evaluating oil and gas prospects, and/or overseeing geophysical activities on domestic projects in Texas, Louisiana, Mississippi, Kansas, Oklahoma, and Alaska; and international projects in Venezuela, Brazil, Jordan, and near the South Caspian Sea. In prior years Mr. Wilson held positions of Senior Staff Geophysicist at Anadarko Petroleum Corporation in Oklahoma City; Project Leader/Division Geophysicist at Tenneco Oil in Oklahoma City; and Geophysicist at Texaco in New Orleans. He earned a B.S. in Geology from Lamar University in Beaumont, Texas, in 1969.

William Foxall is a seismologist with over 30 years of experience in seismic hazard analysis. He earned an M.S. in geophysics from the University of Washington in 1976 and his Ph.D. in geophysics from the University of California, Berkeley, in 1992. He has been employed at the Lawrence Livermore National Laboratory since 1996, and was at the Lawrence Berkeley Laboratory from 1992 to 1996. His work at the Laboratories has included probabilistic seismic hazard analysis, seismic source physics, nuclear forensics, and interferometric synthetic aperture radar analysis of ground deformation related to CO_2 sequestration, enhanced oil recovery and geothermal. Prior to attending UC Berkeley, Dr. Foxall was a Senior Project Seismologist at Woodward-Clyde Consultants in San Francisco.

John Henry Beyer is a Geophysicist in the Earth Sciences Division at Lawrence Berkeley National Laboratory, and is the Program Manager for the West Coast Regional Carbon Sequestration Partnership (WESTCARB) projects in California and Arizona. Dr. Beyer earned a Ph.D. in Engineering Geoscience from the University of California at Berkeley in 1977, an M.A. in Geophysics from Washington University in St. Louis, and a B.S. in Physics from Lafayette College in Pennsylvania. Before returning to Berkeley Lab in 2007, he spent seven years at the California Energy Commission managing energy-related research projects funded by the Public Interest Energy Research (PIER) Program. As an independent consultant he managed geophysical exploration surveys of geothermal areas in Indonesia, the Azores, and Japan. He was the General Manager of a 50-employee company that developed innovative geophysical capabilities and performed magnetotelluric surveys to explore for geothermal and oil resources. This company was a spin-off from Woodward-Clyde Consultants in San Francisco, where he worked as a Senior Project Scientist developing geophysical data analysis techniques and managing geothermal resource exploration.

Appendix 2

Seismic Monitoring Stations

This map shows the proposed injection well location (near MH1); locations of two temporary seismic monitoring stations, MH1 and MH2 (yellow pins); and very tentative locations for four permanent seismic monitoring stations (green and red pins).

The two temporary stations were installed by LBNL on May 18, 2010, for the purpose of measuring seismic noise (vibrations) from the windmills and other local sources, and to see if any microearthquake events are recorded at the gain settings used. The intent is to leave the instruments in the field for about two months to acquire data that will help to determine specifications for a permanent microseismic monitoring array.

The final locations for permanent seismic monitoring stations will depend on several factors, including an appropriate distribution around the well site, low vibration noise from cultural sources, line-of-sight radio telemetry for data transmission, land owner agreements, ease of access, security, and avoidance of interference with farmers, ranchers, and wind turbine operators.

Acknowledgment/Auspices

This work was partially supported by the U.S. Department of Energy and LBNL under Contract No. DE-AC02-05CH11231

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Rec'd 6/25/10

Vulnerability Evaluation Framework Review [1]

Background

In 2008, the U.S. Environmental Protection Agency (EPA) published the "Vulnerability Evaluation Framework" (VEF) identifying factors that should be considered in the geologic sequestration of carbon dioxide (CO_2).[2] As stated in the VEF document, it is not official EPA regulatory guidance, but is designed to frame site specific considerations that may require more in-depth evaluation at a geologic sequestration project. The VEF is useful in helping identify conditions that could increase the potential for adverse impacts to occur from commercial-scale geologic sequestration of carbon dioxide.

As stated in the VEF, attempting to quantify risks potentially associated with geologic sequestration will become more feasible as information is collected from pilot- and commercial-scale projects. The Northern California CO_2 Reduction Project (NCCRP) is a small-volume injection project with the objective of demonstrating the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley. The project will yield data and information that will be informative to future analyses of risk. As such, many of the components identified in the VEF for commercial-scale projects do not apply or are of marginal applicability to the small-scale NCCRP.

The VEF identifies three components that could increase vulnerability to adverse impacts of a sequestration project. These include

- ✓ Geologic sequestration system and geologic attributes,
- ✓ Spatial area of evaluation, and
- ✓ Potential impact categories and receptors.

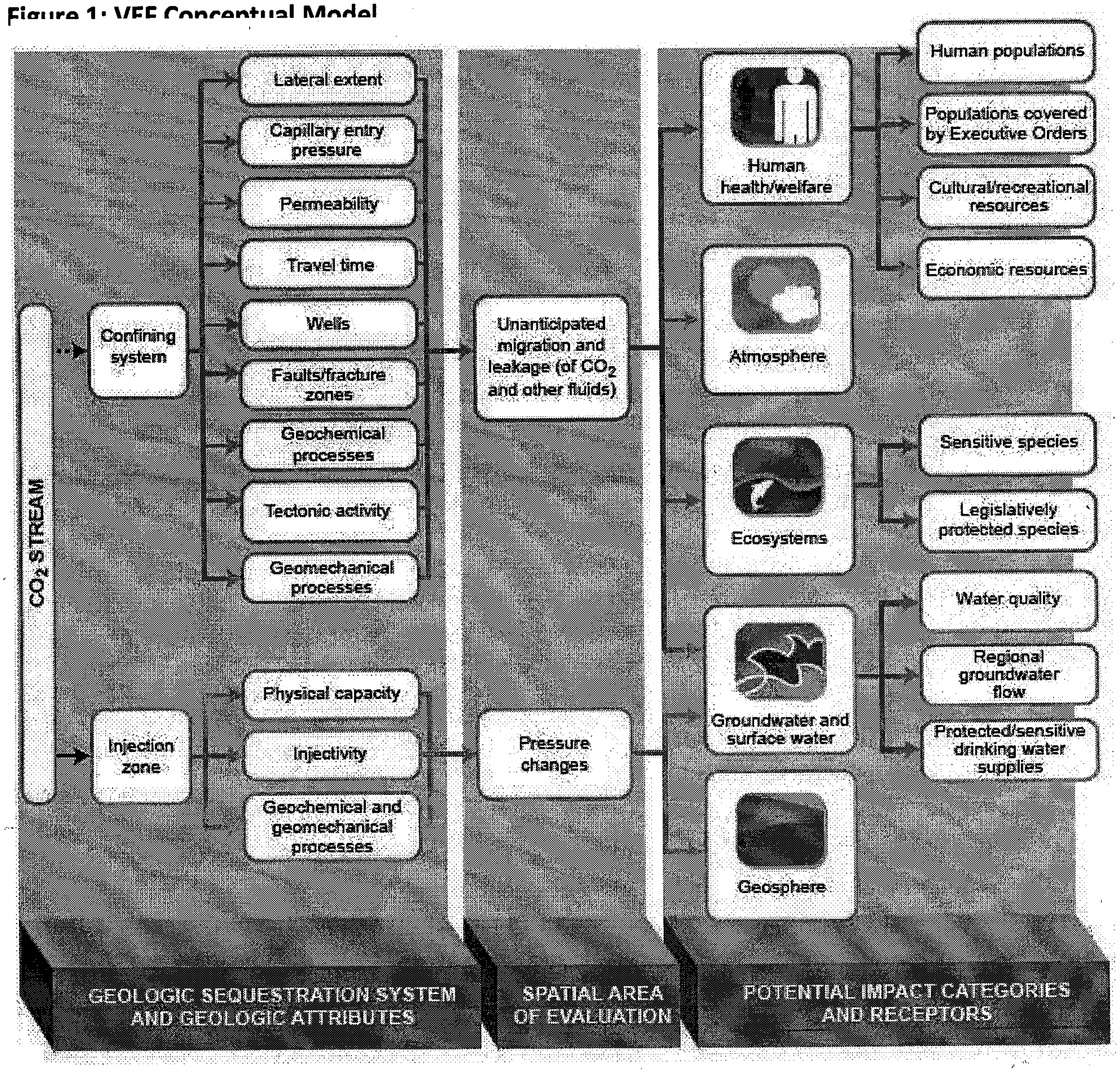
Figure 1 VEF Conceptual Model, is from the VEF document and shows the overall relationship among potential subcomponents of a sequestration project.

Many of the considerations identified in the VEF are addressed for the NCCRP in a Class V Underground Injection Control Permit Application (UIC Permit Application) submitted to the EPA or in an Initial Study submitted to Solano County in support of a Conditional Use Permit (CUP). Copies of both the UIC Permit Application and the Initial Study are available at the Solano County Department of Resource Management. Most topics identified in the VEF are discussed here briefly. Where germane, references are made to the UIC Permit Application and the Initial Study.

[1] Prepared by Fritts Golden, Senior Associate, and Emily Capello, Associate, Aspen Environmental Group, from information in the referenced Initial Study, UIC Permit Application, and Potential Induced Seismicity Report. June 2010.

[2] *Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide*. USEPA. July 10, 2008. EPA430-R-08-009. Available at

Figure 1: VEF Conceptual Model



Source: *Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide,* July 10, 2008, USEPA, EPA430-R-08-009, Figure 3.1, page 13

1. Geologic Sequestration System and Geologic Attributes

The VEF characterizes the geologic sequestration system in terms of (a) the CO_2 stream that is to be held within (b) an underground confining system and introduced into (c) the injection zone.

(a) CARBON DIOXIDE STREAM. When a CO_2 stream is captured at an industrial source, it may have various impurities entrained in it. The effects of these impurities need to be considered

Relationship to Project: The NCCRP would use a commercial or better grade (e.g., food-grade) of CO_2 from a commercial supplier in the region. This would be delivered to the site by tanker trucks during the injection part of the project. Because of the quality of the CO_2, potential adverse impacts from impurities in the CO_2 would not be expected.

- *For additional details regarding the CO_2 see Section 1.9 (CO_2 Storage Tanks) of the Initial Study.*

CO_2 can be considered a hazardous material because of its irritant and asphyxiant characteristics. It is heavier than air and tends to sink to low elevations, displacing air. After analysis, all potential impacts of the small-volume injection project are found to be less than significant with proposed mitigation. Additionally, C6 Resources will install a CO_2 monitoring system at selected locations on the pad and/or provide individual personal monitoring devices to warn site workers of high CO_2 levels. They will also be instructed in leaving the site and assembling at a higher elevation nearby.

- *CO_2 hazards are addressed in Section 3.7 (Hazards and Hazardous Materials) of the Initial Study.*

(b) CONFINING SYSTEM. The confining system for CO_2 is the geologic formation, or group of formations, composed of impermeable or less permeable material overlaying the injection zone. The confining system acts as a barrier to the upward flow of fluids. A variety of geologic attributes influence the potential for unanticipated migration and leakage past the confining system, including lateral extent, capillary entry pressure, permeability, travel time, wells and other artificial penetrations, faults/fracture zones/tectonic activity, and geochemical and geomechanical processes. The VEF approach for considering the confining system includes:

Establish presence of confining system over necessary lateral extent.

Relationship to Project: As the NCCRP is a small-volume project, the lateral extent of the confining system is significantly greater than the geologic sequestration footprint, which would only extend over a radius of about 350 feet from the point of injection into the sandstone formation. There are five potential "pairs" of sandstone/shale strata that form multiple, stacked confining interval/injection interval combinations beneath the test site. The potential major injection interval sandstones are separated by thick shales of marine origin, which will provide the laterally extensive seals for the pilot. Additionally, the objectives of the project are to appraise and establish the presence of confining shales and permeable injection interval sandstones beneath the Montezuma Hills synclinal structure (within the Sacramento basin). Prior to authorizing CO_2 injection, the EPA would evaluate the geologic and geophysical data obtained during well drilling.

- *Additional information is found in Section G.1 (Injection and Confining Zones) of the UIC Permit Application.*

Capillary entry pressure. The capillary entry pressure is defined in the VEF as the added pressure that is needed across the interface of two immiscible (non-mixing) fluid phases (e.g., supercritical CO_2 and brine) in order for CO_2 to enter the confining system. Elevated vulnerability may be associated with exceedance of the confining system capillary entry pressure.

Relationship to Project: Drilling and testing the wells will confirm the stratigraphy beneath the injection site, including characterizing the geologic material and the thickness of each formation. The capillary entry pressure for the NCCRP will be regulated by the UIC permit issued by EPA; it will be determined by EPA after the agency evaluates data collected during development of the wells. The project may include cased-hole testing to further characterize the injection interval sandstones

- *For additional information see Section I.2 (Cased-Hole Testing Program) of the UIC Permit Application.*

Permeability. Permeability refers to the ability of a geologic material to allow transmission of fluid through pore spaces within the rock. Elevated vulnerability may be associated with geologic materials with a high permeability, one greater than clay, shale, or siltstone.

Relationship to Project: Five potential "pairs" of strata form the confining interval /injection interval (i.e., shale/sandstone) combinations. They are, in stratigraphic order, shallowest to deepest:

- Nortonville Shale/Domengine Sandstone
- Capay Shale/Hamilton Sandstone
- Meganos Shale/Anderson Sandstone
- Anderson Shale/ Upper Martinez Sandstone
- Martinez Shale/Martinez123 Sandstone

  - *For additional information see Section G.1 (Injection and Confining Zones) and Attachment G (Geologic Data on Injection and Confining Zones) of the UIC Permit Application.*

Travel time. Travel time refers to the interval of time that is required for a fluid (e.g., CO_2 or brine) to migrate across the thickness of the confining system. Travel times that compromise the integrity of the project are considered to result in elevated vulnerability.

Relationship to Project: Computer modeling of CO_2 migration has been performed. However, the project is a pilot project and the objectives of the project are to appraise and establish the presence of confining shales and permeable injection interval sandstones beneath the Montezuma Hills synclinal structure (Sacramento basin). Additional data collected during well drilling will be used to refine models and to better understand the confining systems, including travel time.

- *UIC Application Section N.4 (Estimation of Pilot Injection Duration) and Section N.5 (Plume movement) discusses the modeling performed for the pilot injection.*

Evaluate integrity of the confining system.

Wells. Wells (and other artificial penetrations such as boreholes) may serve as conduits for fluid movement and hence could result in elevated vulnerability to adverse impacts.

Relationship to Project: No recorded wells penetrate the Confining Zone or the Injection Zone in the vicinity of the project. This eliminates known potential artificial migration pathways to the surface or between formations. (See Attachment B Maps of Well/Area and Area of Review from the UIC Permit Application).

Given the relatively small quantity of CO_2 that would be injected and the limitations on capillary entry pressure stipulated in the UIC permit, it is highly unlikely that the CO_2 would migrate or the project would compromise the integrity of the geology or result in elevated vulnerability.

Faults/fracture zones. Faults are breaks in the Earth's crust that occur when the crustal rock is either compressed or pulled apart, and slippage has occurred across the break. A fracture is any local separation or discontinuity plane in a geologic formation that divides the rock into two or more pieces, but no slippage has occurred.

Relationship to Project. The seismicity of the San Francisco Bay area is concentrated along transverse faults associated with movement of the Pacific Oceanic plate in a northward direction relative to the North American continental crustal plate. More than ninety percent of the seismic events located within the project vicinity are deeper than 8 miles (13 kilometers), well below the formations of interest for the pilot test.

- *Seismic history of the project vicinity and the region are discussed in the UIC Permit Application, see Section F.1.3 (Seismicity).*

Geochemical processes. Geochemical processes are chemical reactions that may cause alterations in mineral phases. Mineralogy and pH (scale of acidity-alkalinity)that favor the formation of conduits in the confining system, by dissolution and/or decreasing molar volume, increase vulnerability; those chemical reactions that do not favor the formation of conduits through dissolution and/or increases in molar volume decrease vulnerability.

Relationship to Project. Fluid samples will be recovered from each of the major sand intervals. These will be used to determine formation fluid characteristics. A number of tests will be run on the samples including mineral composition and pH.

- *See Section I.1.4 (Open-hole Well Logging Program) of the UIC Permit Application.*

Tectonic activity. Tectonically active settings may be more likely to have faults and/or fractures that may be provide pathways for migration of CO_2. Areas with seismic hazard ratings that indicate the potential for seismicity to cause adverse impacts are considered to have elevated vulnerability.

Relationship to Project. The seismicity of the San Francisco Bay area is concentrated along transverse faults associated with movement of the Pacific Oceanic plate in a northward direction relative to the North American continental crustal plate. Ninety percent of the seismic events located within the project vicinity are deeper than 8 miles (13 kilometers), well below the formations of interest for the pilot test.

- *Seismic history of the project vicinity and the region are discussed in the UIC Permit Application, see Section F.1.3 (Seismicity).*

Geomechanical processes. These are processes that may alter the structural integrity of geologic material. Appropriate evaluation metrics for this attribute include fracture pressure, fracture/fault reactivation pressure, and orientation of the fracture or fault relative to the orientation of the principal regional stress regime. If the fracture pressure and the fracture/fault reactivation pressure (multiplied by a safety factor) are exceeded, vulnerability is considered to be elevated. It should be noted that geomechanical processes occur at a continuum of scales. For example, potential impacts such as deformation of geologic formations can occur without necessarily adversely affecting the integrity of the confining system.

Relationship to Project. Mini-frac injection tests will be used to estimate the fracture closure pressure of the formation. The tests will provide the in-situ minimum stress that will define a maximum bottomhole pressure for injection tests for reservoir characterization and for CO_2 injection.

- *See UIC application Section I.2.2.1 (Mini-frac Injection Tests) for discussion of the use of the mini-frac injection tests to estimate the fracture closure pressure of the formation.*

(c) INJECTION ZONE. The injection zone is a geologic formation of sufficient areal extent, thickness, porosity, and permeability to accommodate the CO_2 injection volume and injection rate. This zone is characterized by its physical capacity, injectivity, and geochemical and geomechanical processes.

Physical capacity.

Relationship to Project: The Central Valley saline formations are estimated to have storage capacity of 50 to 200 gigatonnes of CO_2. This project would inject up to 6,000 tonnes (i.e., 0.000006 gigatonnes) of CO_2. This is a very small volume in relation to the target formation. One of the major objectives of the project is to demonstrate and evaluate the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley.

- *See UIC application Section 1.8 (Project Benefits and Objectives)*

Injectivity.

Relationship to Project: The injectivity of the geologic formation is unknown at this time. During the injection process, it is planned that as much as approximately 300 hundred tons of CO_2 per day would be introduced into the formation; however, the actual rate will depend on formation characteristics and may be much lower. The operational factors of the injection will be reviewed and revised as well data and baseline data become available.

- *Section N.3 (Injection Prediction) of the UIC Permit Application includes information regarding the simulation models which predict the maximum injection rate profile over time.*

Geochemical and geomechanical processes.

Relationship to Project: Geochemical modeling for the injection of CO_2 into brine indicates that the pH in the formation brine should not drop below a value of about pH 5.3, due to the buffering provided by naturally occurring reactive minerals in subsurface formations.

- *See Attachment P (Monitoring Program) of the UIC Permit Application.*

2. Spatial Area of Evaluation: Geologic Sequestration Footprint

The geologic sequestration footprint is based on the size and shape of the CO_2 subsurface plume and the pressure front associated with the plume.

Relationship to Project: The NCCRP is a small-volume injection project. The edge of the plume is expected to have a radius of about 350 of feet from the point of injection, which is over 2 miles below the surface. The plume size (sequestration footprint) is not significant given (1) it is in the range of a few hundred feet away from the point of injection, (2) the likely permeability in the injection interval and (3) the limited injected volume (less than 6,000 tonnes). Well injectivity is largely unknown for the time being, due to uncertainties on injection interval properties (porosity, permeability, relative permeability, rock compressibility, fracture pressure, etc.) and well completion quality (well skin). This injection prediction work is therefore focused on identifying the possible injection rate potentials in a few subsurface scenarios, which bound expected conditions. This is true for the plume movement as well.

- *See Section N.5 (Plume Movement) of the UIC application, which addresses modeling of the CO_2 plume.*

3. Potential Impact Categories and Receptors.

Unanticipated CO_2 migration or leakage, or changes in subsurface pressure, could potentially cause adverse impacts to human health and welfare, the atmosphere, ecosystems, groundwater and surface water, or the geosphere. As the project is a small-volume project, adverse impacts are not expected to occur.

- *See Initial Study in general.*

Potential Human Health and Welfare. The VEF states that the vulnerability of a population to the release of CO_2 is affected by the population's size and sensitivity to CO_2 and the proximity to and concentration of the release. Potential receptors are human populations (including populations covered by Executive Orders), cultural and recreational resources, and economic resources.

Relationship to Project: As stated in the Initial Study, the nearest sensitive receptor is one mile away from the injection site. No impacts to any sensitive receptors, including populations covered by Executive Orders (environmental justice populations), would occur.

The nearest known cultural resource is located 0.75 miles from the project site. The nearest recreational resource is located approximately 2.3 miles from the project site. No impacts to cultural resources or recreational resources are expected.

The CO injection is not expected to preclude existing land use or subsurface activities at the site.

- *See Initial Study in general. In particular see Section 3.5, (Cultural Resources), Section 3.14, (Recreation), and Section 3.9 (Land Use and Planning).*

Potential Atmospheric Impacts. As the VEF states, releases of CO_2 from the geologic sequestration could reduce the benefits of capturing CO_2.

Relationship to Project: The project is a small-volume project to demonstrate the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley. Significant releases of CO_2 are not expected. Some releases will occur when equipment is purged or during transfer of CO_2 from delivery tankers to storage tanks

- *See the Project Description in the Initial Study. Air quality impacts are discussed in Section 3.3 of the Initial Study.*

Potential Ecosystem Impacts. Potential effects could impact sensitive species and legislatively protected species.

Relationship to Project: An environmental review of impacts to sensitive species and legislatively protected species concludes that all impacts would be less than significant. These species are not present on the site. Potential impacts of the project on deep geologic ecosystems are unknown.

- *See Initial Study Section 3.4 (Biological Resources).*

Potential Groundwater and Surface Water Impacts. Potential effects could impact water quality, regional groundwater flow, and protected/sensitive drinking water supplies.

Relationship to Project: The CO_2 injection would occur at nearly 2 miles below potable water aquifers in the area and would be separated by several thick impervious shale formations. Any re-injection of produced brine into the storage formations would not affect potable groundwater quality. Migration of CO_2 to groundwater aquifers is unlikely, given the small volume of CO_2, the depth of the injection, the multiple casings and cement of the well bores, and the multiple thick shale formations separating the injection zone from aquifers. However, at the request of Solano County, well water will be sampled and tested to determine if there is a change. There is no surface water near the site, but appropriate best management practices applicable to the project would be incorporated in the project to minimize any potential impacts to surface water.

- *See Section 3.8 (Hydrology and Water Quality), in the Initial Study and Attachment D, Maps and Cross Sections of Underground Source of Drinking Water of the UIC Permit Application.*

Potential Geosphere Impacts. As stated in the VEF, changes in subsurface pressure from geologic sequestration could potential cause fracturing or reopening of faults and fracture zones.

Relationship to Project: Pressure in the geologic formations at 2 miles deep is on the order of 5,000 pounds per square inch (psi). Modeling indicates that at 1.8 miles from the injection well, the CO2 injection temporarily will add approximately 11 psi, an extremely small increase. In addition, the nearest fault is approximately 3 miles from the injection site, and the added pressure at that distance is expected to be even less.

- *Potential impacts related to seismic activities are addressed in the Initial Study (Section 3.6 Geology and Soils). See also a report on potential induced seismicity report:* Draft Preliminary Report on the Potential for Induced Seismicity Related to CO2 Injection, Montezuma Hills Pilot Test, Solano County, *CA, prepared by Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory.*

Mitigation and Monitoring

Relationship to Project: Because the CO_2 volume to be injected is small, the site is remote from sensitive receptors, and the injection point is over 2 miles deep, the NCCRP results in low vulnerability. Adverse impacts are not expected.

Monitoring will be a key aspect of the project. Data would be collected on how CO_2 behaves within the formation and on the nature of the geology and its characteristics. Baseline data collection would be performed to evaluate the composition, physical properties, pressure and temperature of native fluids found in the saline formation and near-surface groundwater. Baseline measurements would be compared to data collected during and after CO_2 injection to look for changes in geochemistry, hydrochemistry, and fluid pressures, indicating potential leakage from the target injection formation into overlying formations. Monitoring would be ongoing during and after the injection and a post-injection geophysics evaluation will be performed.

- *Attachment P Monitoring Program of the UIC Permit Application provides additional monitoring details.*

rec'd 6/4/10

Memorandum

DATE: June 3, 2010

TO: Solano County

FROM: Elizabeth Burton, Technical Director, WESTCARB

RE: Draft Preliminary Report on the Potential for Induced Seismicity Related to CO_2 Injection, Montezuma Hills Pilot Test, Solano County, CA

Scientists at Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL) have prepared a draft preliminary report that addresses the issue of the potential for induced seismicity related to the proposed permitting of a well and 6000 ton CO_2 injection for the Northern California CO_2 Reduction Project.

We are submitting a draft version of this document to you, which we expect to finalize and issue as a joint LBNL-LLNL report in the near future. We would welcome your comments and suggestions on the draft document.

Since completion of the draft, a couple of items that require clarification have come to our attention:

1. Recently, and since the preparation of the draft report, the California Geological Survey (CGS) released a digital map titled, *2010 Fault Activity Map of California*, which shows the locations of known faults and age ranges of surface rupture or displacement. A screen shot of this map zoomed in to the Montezuma Hills area is shown in the figure below.

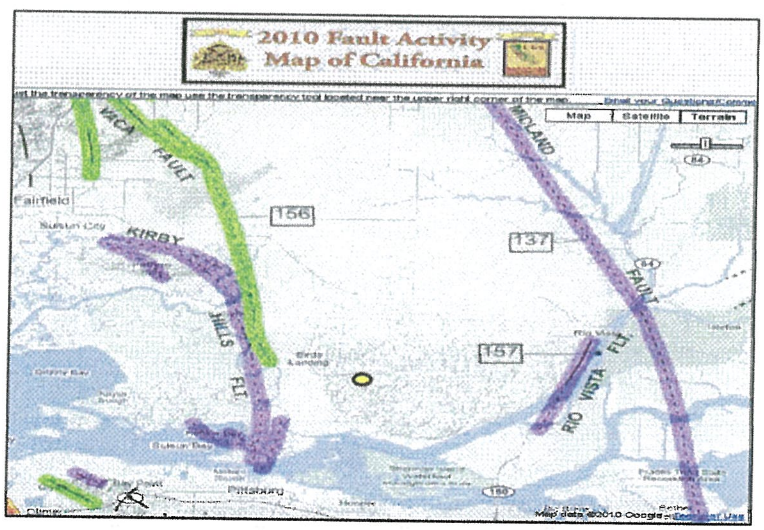


Figure 1: Screen shot of the CGS *2010 Fault Activity Map of California* for the Montezuma Hills area. Yellow dot is the proposed well location. http://www.quake.ca.gov/gmaps/FAM/faultactivitymap.html

The locations of the faults described in this report were obtained from an in-press version of this map, however, the information on the age of fault activity was not included. In particular, the Kirby Hills fault, described as active in our report, is not classified as historically active because there is no evidence of displacement within the past 700,000 years. It is important to note that the CGS classification for activity is based on surface displacement; whereas the small magnitude (<4) seismic activity for this fault recorded in the last 32 years, as described in the report, is very deep (9-17 mi).

2. The Kirby Hills and Vaca faults appear to be designated with other names in previous reports (e.g, Kirby Hills-Vaca fault zone, Montezuma-Vaca fault zone) and we are in the process of crosschecking with the authors of these reports.

Please feel free to contact me for further information. Thank you for your time and attention.

Contact information:

Dr. Elizabeth Burton

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Rec'd 6/4/10

PRELIMINARY REPORT ON THE POTENTIAL FOR INDUCED SEISMICITY RELATED TO CO_2 INJECTION, MONTEZUMA HILLS PILOT TEST, SOLANO COUNTY, CA

Larry Myer[1], Laura Chiaramonte[2], Thomas M. Daley[1],
Katie Boyle[1], Danny Wilson[3], William Foxall[2], and John Beyer[1]

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[2] Lawrence Livermore National Laboratory, Livermore, CA
[3] Consultant, Houston, TX

Executive Summary

The objective of this technical report is to analyze the potential for induced seismicity due to a proposed CO_2 injection pilot test in the Montezuma Hills. We reviewed currently available public information including 32 years of recorded seismic events, locations of mapped faults, and estimates of the stress state of the region. We also reviewed proprietary geological information acquired by Shell, including seismic reflection imaging in the area, and found that the data and interpretations used by Shell are appropriate and satisfactory for the purpose of this report.

The closest known fault to the proposed injection site is the Kirby Hills Fault. The Shell seismic data also indicate two unnamed faults in the area. The Kirby Hills fault appears to be active, and microearthquakes as large as M3.7 have been associated with the fault in the site area over the past 32 years. Most of these small events occurred 9-17 miles (15-28 km) below the surface, which is deep for this part of California. The geographic locations of the many events in the standard seismicity catalog for the area are subject to considerable uncertainty because of the lack of nearby seismic stations, and so attributing the recorded earthquakes to motion along any specific fault is also uncertain. Nonetheless, the Kirby Hills Fault is the closest to the proposed injection site and is therefore our primary consideration for evaluating the potential seismic impacts, if any, from injection. Our planned installation of seismic monitoring stations near the site will greatly improve earthquake location accuracy.

The stress state (both magnitude and direction) in the region is an important parameter in assessing earthquake potential. Although the available information regarding the stress state is limited in the area surrounding the injection well, it is consistent with strike-slip or reverse faulting. We found large variation (uncertainty) in stress estimates, leading to low confidence in our conclusions regarding which fault segments are optimally oriented for potential slip induced by pressure changes. Uncertainty in the stress state can be substantially reduced by measurements we plan to make when wells are drilled at the site.

Injection of CO_2 at about two miles depth will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly. Pressure changes have been

predicted quantitatively by numerical simulation models of the injection. Based on these models, the pressure increase on the Kirby Hills Fault at its closest approach to the well due to the injection of 6,000 metric tons of CO_2 would be only a few pounds per square inch (psi), which is a tiny fraction of the natural pressure of approximately 5,000 psi at that depth. The likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded earthquakes are concentrated because it is unlikely that such a small pressure pulse would propagate downwards over any appreciable distance.

In response to the specific question of the likelihood of the CO_2 injection causing a magnitude 3.0 (or larger) event, this preliminary analysis suggests that no events would be expected. We do note that natural earthquake events larger than magnitude 3.0 have occurred in this area and would be expected to occur again regardless of the proposed CO_2 injection.

Introduction

The objective of this report is to analyze the potential for induced seismicity due to a proposed CO_2 injection pilot test in the Montezuma Hills.

To address this question, it is necessary to understand the present day stress state, its relationship with the preexisting faults in the area, and the effects of pressure changes resulting from injection activities. Therefore, currently available information on faults and the stress state in this region has been assembled and used in conjunction with preliminary simulation data to assess the potential for slip on the preexisting faults. Finally, recommendations are made for specific actions to address the potential for induced seismicity due to injection operations.

Faults in the Vicinity of the Montezuma Hills

Figure 1 shows mapped faults in the vicinity of the proposed small-scale injection project. Information is reproduced from the California fault map compiled by the California Geological Survey (CGS) (Jennings and Bryant, 2010), which is the state agency responsible for assessing the natural seismic hazard potential throughout California. Also shown are a small subsurface fault, the Sherman Island Fault, and the blind Midland fault, both identified in a report supporting the California Department of Water Resources Delta Risk Management Strategy (DRMS) (URS Corporation/Jack R. Benjamin & Associates, 2007).

Kirby Hills Fault

The trace of the Kirby Hills Fault (KHF) on the CGS fault map is located approximately 3 miles (5 km) west of the proposed injection site (Figure 1). Based on seismic reflection data along the Sacramento River and on microseismicity, Parsons et al. (2002) concluded that the KHF zone is active, predominantly strike-slip (SS), and dips 80°–85° east. Figure 2 shows the earthquakes recorded by the USGS/UC Berkeley Northern California Seismic Network (NCSN) between 1974 and 2001, relocated by Parsons et al. and assumed to be associated with the KHF zone. Microearthquake focal mechanisms presented by Parsons et al. reveal both strike-slip and reverse components of fault slip, with the reverse component increasing to the north of the proposed injection well location. The majority of the earthquake hypocenters located by Parsons et al. lie between 9 and 17 miles (15 and 28 km) in depth, which is unusually deep for this region of California[1].

[1] A recent evaluation of the Kirby Hills Fault zone by the California Geological Survey (Jennings and Bryant, 2010) finds no evidence for surface displacement along the fault trace since the early Quaternary period (>700,000 years ago). See Addendum for more information.

Midland Fault

The Midland Fault (Figure 1) is located about 10 miles (16 km) east of the proposed injection site. It is described in the DRMS report as an approximately 37 miles (60 km) long, north-striking and west-dipping blind fault underlying the central Delta region. It is interpreted as an early Tertiary, normal fault that was reactivated in the late Cenozoic as a reverse fault. The Midland fault has been characterized primarily from natural gas exploration well data and analysis of overlying folding. The fault breaks into a series of northwest-striking splays associated with a series of active and abandoned gas fields in the Sacramento Valley between the towns of Rio Vista and Woodland (URS Corporation/ Jack R. Benjamin& Associates, 2007).

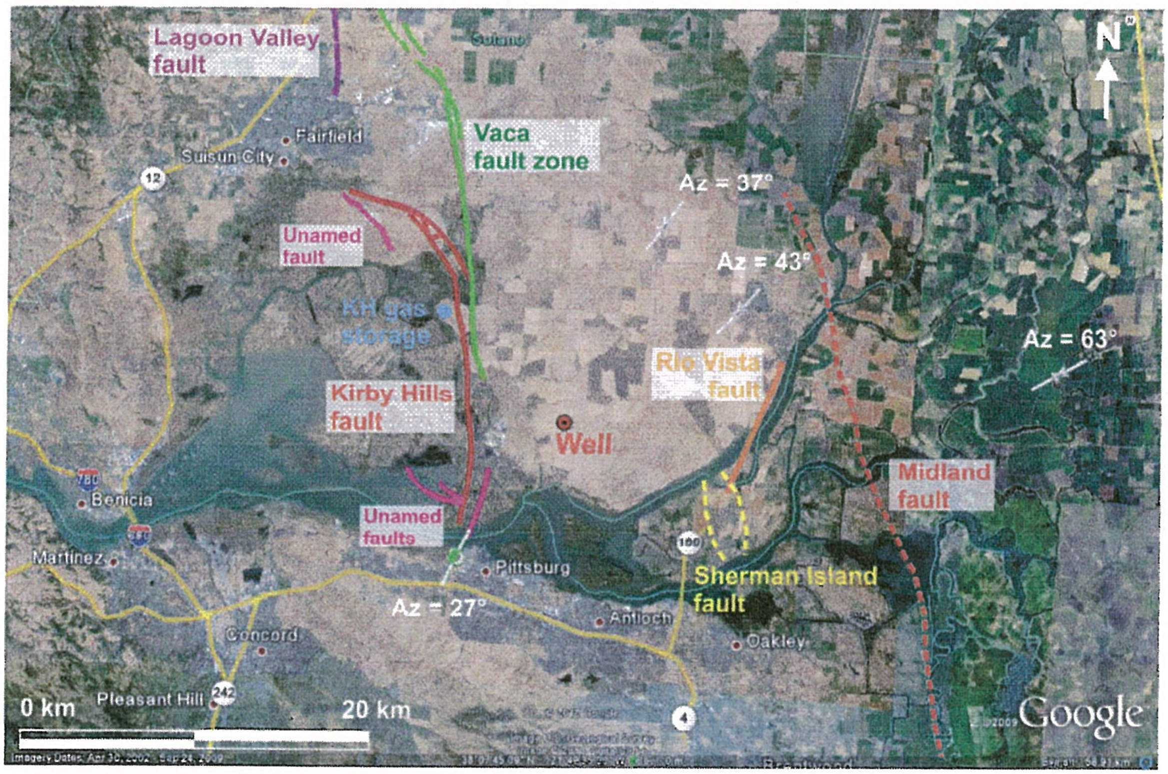

Figure 1 Faults and maximum horizontal stress (S_{Hmax}) direction in the area under study. Solid lines correspond to faults with surface expression taken from the CGS fault map (Jennings and Bryant, 2010); dashed lines are subsurface faults from the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007). S_{Hmax} directions are plotted as short gray lines (Heidbach et al., 2008). S_{Hmax} symbols with a green dot are determined from single earthquake focal mechanisms (FMS) The lines without a green dot come from borehole breakout observations. The proposed injection site is indicated with a red dot labeled Well.

Sherman Island Fault Zone

The Sherman Island (SI) fault zone is located approximately 5 miles (8 km) southeast of the proposed injection site (Figure 1). According to the DRMS report, this fault has been identified only in the subsurface and was active in late Cretaceous-early Tertiary time. To date, the fault has not been studied for evidence of Quaternary reactivation. The CGS fault map shows the Rio Vista fault at the same location as the Sherman Island fault, but the Rio Vista fault appears to have a different strike than that of the Sherman Island fault. CGS considers the Rio Vista fault to be inactive, based on lack of evidence for Quaternary movement.

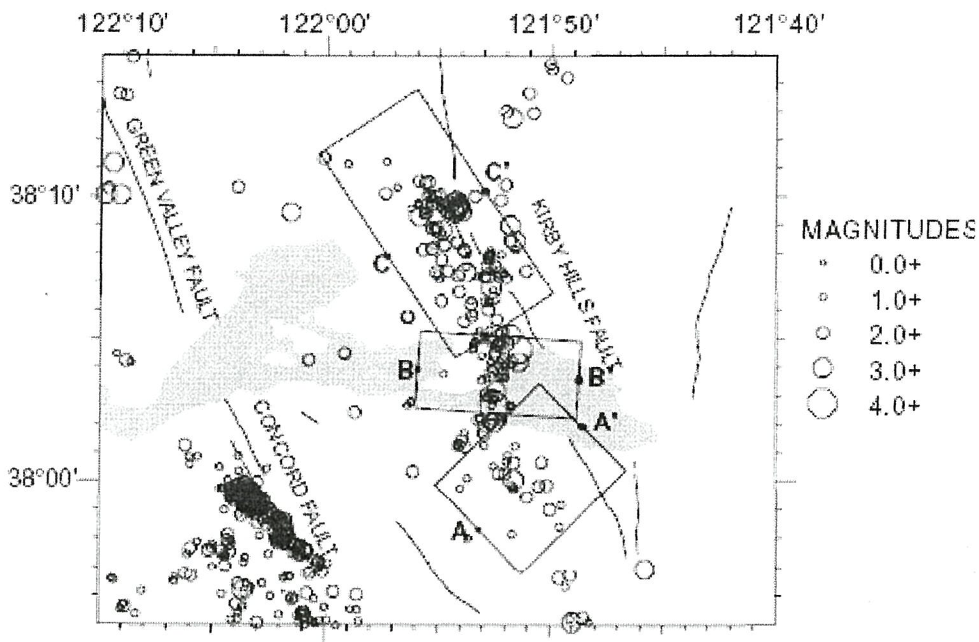

Figure 2: Kirby Hills Fault zone and associated seismicity from 1974-2001, recorded by the Northern California Seismic Network and relocated by Parsons et al. (2002).

Natural Seismicity in the Project Area

The microearthquakes relocated by Parsons et al. (2002) and assumed to be associated with the KHF zone (Figure 2) were discussed above. Figure 3 shows the NCSN catalog locations of magnitude 2.5 and greater earthquakes within the area immediately surrounding the project site for the period January 1, 1978 through January 28, 2010. The largest event recorded within the area during this period has a catalog magnitude of 3.7 and depth of 22 km (14 miles). Preliminary examination of the recorded NCSN data indicates that the uncertainties in many of the catalog locations may be relatively large, due primarily to the scarcity of recording stations in the surrounding area, particularly to the east of the injection site (Figure 3). Therefore, a focused study of the locations and mechanisms of the better recorded events should be carried out to better define the relationship of the microearthquakes to the KHF in the immediate vicinity of the site.

The largest earthquake recorded in the larger area considered by Parsons et al. (Figure 2) was M 4.3. This event was located at a depth of 20 km (12 miles) below the confluence of the San Joaquin and Sacramento rivers.

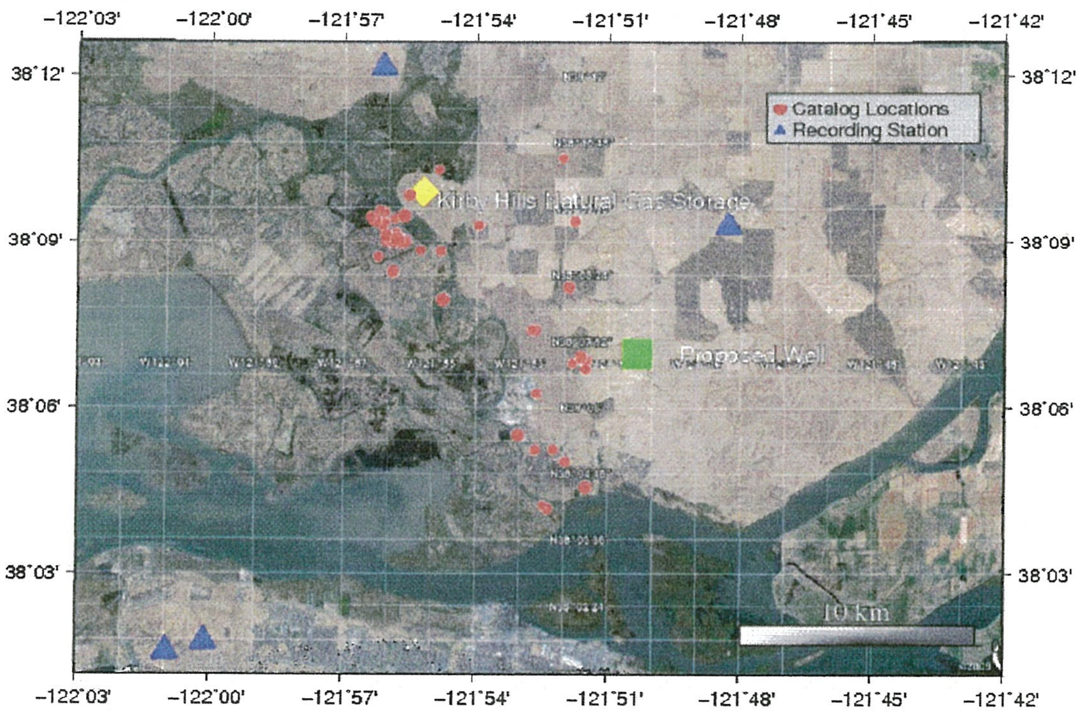

Figure 3. Seismicity with magnitude of at least 2.5 for the period 1/1/78-1/28/10 (red dots) in the area surrounding the injection site (green square) from the NCSN catalog. The largest event had a magnitude of 3.7. Blue triangles are NCSN recording stations.

Seismic Data Interpretation

Shell developed an initial model of the subsurface geologic structure in the vicinity of the project based in part on an internal interpretation of twenty 2-D seismic lines. LBNL has carried out an independent analysis of the seismic data and concurs with the Shell interpretation. As shown in Figure 4, the seismic data indicate that the structures closest to the proposed injection well are two unnamed faults (labeled Fault A and Fault B), and the Kirby Hills Fault.

Fault A is more than 3 miles (5 km) from the proposed injection well at reservoir depth. Neither Fault A nor Fault B reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 m), which indicates that they are not currently active faults. Both faults trend toward the Sherman Island fault, but further work is required to evaluate their possible relationship to the Sherman Island Fault. The seismic data also show that the Kirby Hills Fault is about 3 miles (5 km) from the proposed injection well at reservoir depth. The primary indicator of the Kirby Hills Fault in the seismic data is a "wash-out" of the seismic signals (similar to the expression of the fault in the seismic data along the Sacramento River presented by Parsons et al. [2002]). Improved delineation would require acquisition of additional seismic data.

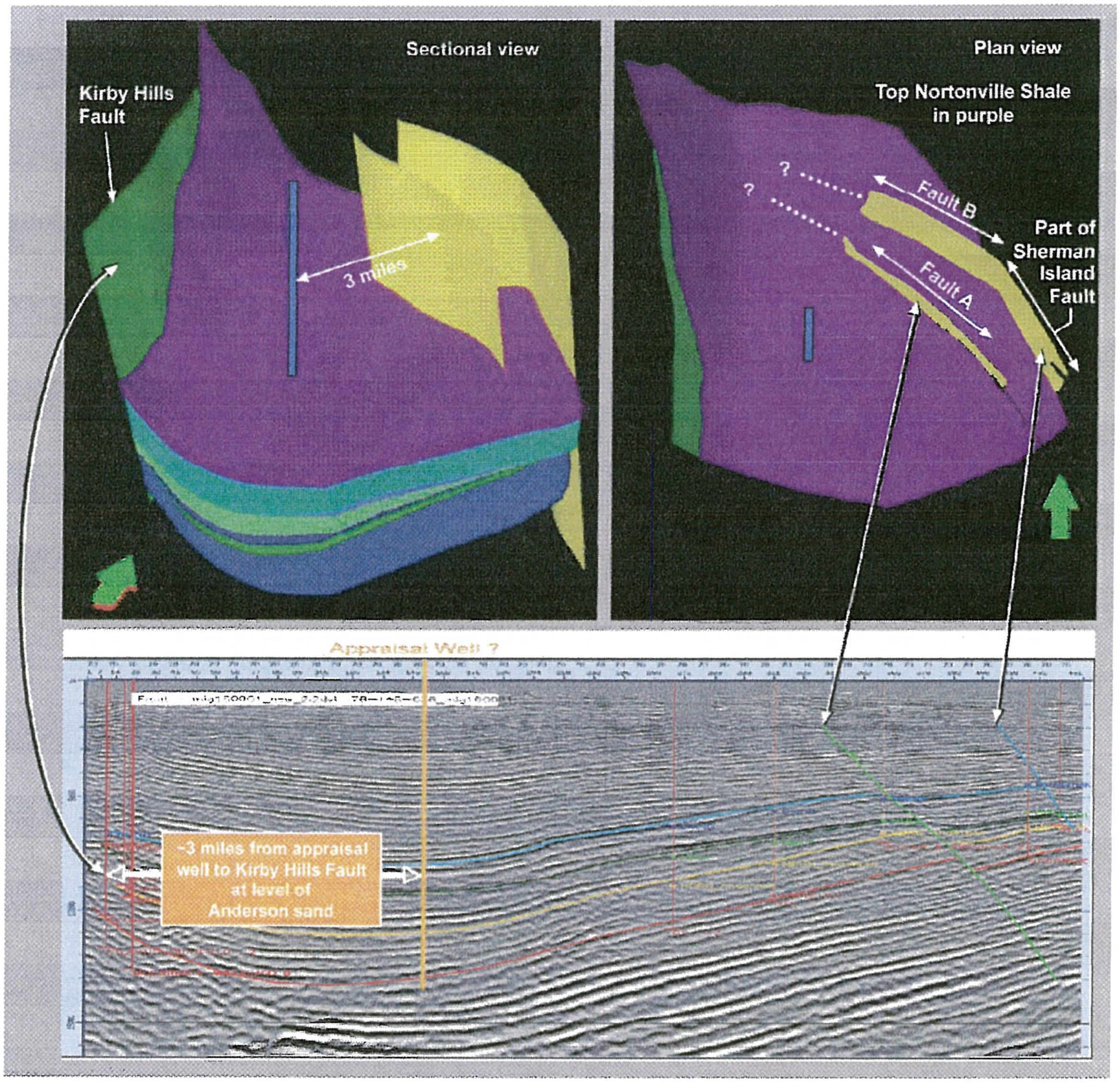

Figure 4: Shell's internal interpretation showing the Kirby Hills Fault, Fault A and Fault B, and site of proposed well.

Stress State

Limited information on the present day stress state was found for this area. Orientations on the maximum horizontal stress were compiled from the World Stress Map (Heidbach et al., 2008). The mean maximum horizontal stress (S_{Hmax}) azimuth is 41°. Measured values (Figure 1) near the proposed pilot well are 20°, 27°, 37°, 43°, 54° and 63°. These orientations were estimated from single focal mechanisms (FMS) (short gray lines with green dot in Figure 1) and borehole breakouts (short gray lines). The FMS analyses also indicated a strike slip (SS) stress regime.

Dr. Haibin Xu from Shell performed a Fracture Pressure Prediction study and found indications from leak-off tests and seismic observations on offsets on the faults, that the stress state could be reverse faulting (RF regime) at the surface and strike slip (SS regime) at depth (Haibin Xu, personal communication, 2010). The limited available information regarding the stress state indicates that the area surrounding the injection well could be an oblique faulting SS/RF environment, consistent with the focal mechanism solutions reported by Parsons et al. (2002). Uncertainty in the stress state can be substantially reduced by measurements made when the proposed well is drilled.

Relationship Between Faults and In-situ Stress

Knowledge of the orientation of the in-situ stresses enables identification of faults that are most prone to movement under that stress regime. This is the first step in evaluating the likelihood of fault movement, which also requires an analysis of the magnitude of stress change required to cause movement on a fault. Under a strike slip (SS) stress state, faults oriented approximately ±30° from the S_{Hmax} direction are most prone to slip. Under a reverse faulting (RF) environment, the optimal direction for movement is sub-perpendicular to the S_{Hmax} direction (Zoback, 2007). However, there are certain values of the in-situ stress tensor that correspond to both SS and RF regimes. If a region is characterized by an SS/RF state of stress, then faults having multiple orientations could be prone to movement at the same time.

Figure 5 shows the faults and stress orientation near the proposed injection well based on currently available data. It also shows the mean S_{Hmax} direction (red line in lower right circle), the optimal direction for movement in a SS regime (dotted green lines), and the optimal direction for movement in a RF regime (blue line).

Comparison of the SS and RF directions with the fault traces shown in Figure 5 suggests that segments of the KHF, the unnamed faults south of Kirby Hills and the (inactive) Rio Vista fault are oriented in directions most favorable for movement. The level of confidence in this conclusion is low, however, due to the large scatter in the stress observations near the injection well, which results in uncertainty in the orientation of the stress field, and due to uncertainty in the geometry of the fault planes at depth. Since the KHF is active, it is assumed that its fault plane is favorably oriented for slip at least in the depth range within which microearthquakes have occurred. It is possible that the in-situ stress orientations change with depth, but additional data are required to support such a hypothesis.

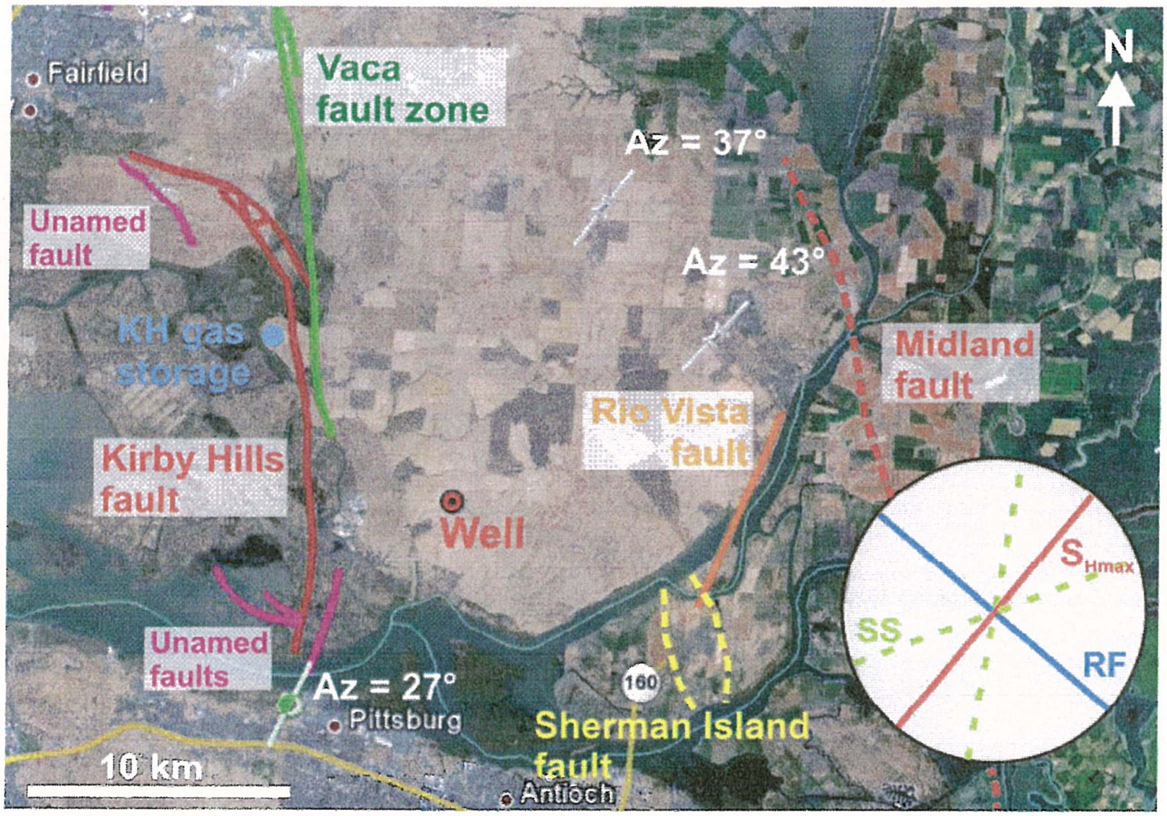

Figure 5: Faults and maximum horizontal stress direction near the proposed injection well (red dot). The circle in the lower right corner shows the mean S_{Hmax} direction (red), the optimal directions for fault movement for SS (green) and for RF (blue).

Relationship Between Faults and Reservoir Pressures

Injection of CO_2 will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly, approaching pre-injection values for situations in which the storage reservoir is very large in comparison to the volume of injected fluid. It is well known that injection operations can induce fault movement if pressures in a fault zone are increased to a level where the resistance to slip on the fault is exceeded. Faults with optimum orientation with respect to the natural stress direction, as described in the previous section, will in general require relatively smaller pressure increases than those having other orientations.

Since the Kirby Hills Fault is the active fault closest to the injection test site, we made a preliminary assessment of the potential for slip on this fault due to the pressure increase expected from the proposed volume of injection. Shell has performed a preliminary reservoir simulation to predict pressure increases due to the planned 6,000 metric ton CO_2 injection. The western boundary of this model was placed at about 10,000 feet (1.8 miles, 3 km) from the injection well in the form of a "no-flow" hydrologic boundary condition (equivalent to the assumption of a sealing fault). The simulated increase in pressure at the western boundary of the model is less than 0.08 MPa (12 psi), which corresponds to 0.2% of the hydrostatic pore pressure of about 5,000 psi (34.5 MPa) at the Anderson Formation depth of 2.1 miles (3.4 km). This maximum pressure increase occurred 150 days after injection stopped, with pressures declining thereafter. The Kirby Hills Fault is about 1.2 miles (2 km) farther to the west from the western boundary of the model, and so the pressure increase extrapolated from the model to the fault at a depth of about 2.1 miles (3.4 km) would be considerably less than 12 psi. Even if the fault is optimally oriented for movement at the injection depth, the likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at significantly greater depths, where most of the recorded microearthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards over any appreciable distance (e.g., Segall, 1985).

Discussion

To understand what size of fault can produce a magnitude 3 earthquake, we can use one of the numerous scaling relationships for the magnitude of an earthquake versus the area of slip (e.g., Shaw, 2009; Kanamori, 1977). Using Kanamori (1977), a 250-m (820-foot) radius fault is needed to produce a magnitude 3 earthquake, which would correspond to a circular fault area of ~0.2 km^2 (~0.08 mi^2). This could easily be accommodated by any of the faults discussed above. However, as discussed in previous sections, multiple factors influence the potential for slip on any particular fault. Based on Shell's preliminary reservoir modeling, the faults near the injection well would experience, at most, a very small increase in fluid pressure. Therefore, this preliminary analysis suggests that no slip events would be expected due to the proposed injection.

In general, the greatest increase in storage reservoir fluid pressure occurs in a limited volume around the injection well; for example, Shell's reservoir simulations showed that the region of pressure increase in excess of 30 psi (0.21 MPa) will extend for about 0.6 mile (1 km) in all lateral directions from the well. Review of the seismic reflection data did not reveal any faults within this area. However, if a fault or fracture of 250-m (820-foot) radius does exist this near the well location, the resolution of the existing seismic data is probably not sufficient to detect it. Therefore, based on currently available data, it is not possible to say whether or not a fault or fracture of 250-m radius is present near the proposed well. Once the well is drilled, information will be available to reduce this uncertainty significantly.

As discussed above, the injection operation is not expected to cause slip on the Kirby Hills Fault. However, review of the natural seismicity reveals several naturally occurring earthquakes having magnitudes greater than 3 since the late 1970s. A recurrence analysis has not yet been carried out, but a natural earthquake greater than magnitude 3 will certainly occur eventually in the area, independent of any possible effects of the injection project.

If future injection projects involving larger volumes are considered for this site, a site-specific probabilistic seismic hazard analysis (PSHA) is recommended. PSHA is the calculation of the probability that a particular ground-motion measure (acceleration or velocity) will exceed given amplitude thresholds at one or more places of interest during a specified time period (e.g., Hanks and Cornell, 2008). The first step would be to refine the PSHA for the naturally-occurring seismicity in the area published by CGS/USGS by carrying out more detailed characterization of the local active faults. The second step would be to assess the influence on the seismic hazard of potential induced seismicity associated with a large-scale injection project.

At present, definitive, quantitative statements about the likelihood of induced seismicity are difficult to make because of the present lack of data and uncertainty in the subsurface structure. To improve risk assessment and to begin acquiring the data necessary for analysis, a high-resolution microseismic monitoring network should be installed to detect and locate seismic events that might occur in the site region. This local network would be capable of detecting smaller events than the USGS regional network and provide improved event location accuracy. The network should be integrated into the regional seismic network and installed as soon as possible in order to record the maximum number of naturally-occurring events as a baseline before injection of CO_2 begins.

Conclusions and Recommendations

Initial geologic characterization studies performed to date have identified mapped and unmapped faults and other structural features in the area surrounding the proposed injection well. From an analysis of the available data on in-situ stresses and preliminary reservoir simulations, the likelihood of slip on these faults resulting from the proposed 6,000 metric ton injection is judged to be very low. Examination of the local seismicity shows that natural earthquakes having magnitudes greater than 3 have occurred in the past and consequently are likely to recur in the area regardless of injection operations.

To reduce the uncertainties discussed above (including uncertainties about fault locations and in-situ stress directions), several actions are recommended:

1. Install a microseismic network as soon as possible to begin to compile a high-resolution baseline of natural seismicity and seismicity induced by human activities in the area prior to injection. The network will remain in place to monitor for natural seismicity and any induced seismicity that may occur during injection operations.
2. Upon drilling the injection and monitoring wells, collect information on the in-situ stress state and natural faulting or fracturing near the wells.
3. Prior to injection, reassess the potential for operating conditions during injection to induce significant seismicity and develop a protocol for responding to any significant natural or induced events recorded by the network.
4. During and after injection, carry out additional geomechanical analyses using information obtained during the small scale injection, and develop a PSHA which includes potential induced seismicity at the site.

5. Carry out focused studies to relocate the better recorded microearthquakes listed in the NCSN catalog for the site area and to calculate focal mechanism solutions for selected events. Evaluate the relationship of the relocated earthquakes to the KHF to improve characterization of the fault.
6. Evaluate PSHA results for the Montezuma Hills area in the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007).
7. As part of on-going geologic site characterization studies, collect any additional available data to better characterize the faults in the area. This may include acquiring a 3D seismic survey after injection to augment existing 2D data.

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Zoback, M.D., 2007, Reservoir Geomechanics: Earth Stress and Rock Mechanics Applied to Exploration, Production and Wellbore Stability, Cambridge Press, Cambridge Press, 449 pp.

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Fax: (707) 784-4805

Clifford Covey, Interim Director

May 23, 2010

Michele Dermer
Environmental Scientist, Underground Injection Control
U.S. Environmental Protection Agency, Region 9
75 Hawthorne Street (WTR-9)
San Francisco, CA 94105-3901

Re: C6 Resources LLC –Draft US EPA UIC Permit

Dear Michele:

We appreciate the opportunity to review and comment on the Administrative Draft UIC Permit.

The proposal is subject to a discretionary Land Use Permit approval by the Solano County Planning Commission; thus, subject to the California Environmental Quality Act. The Planning Division has determined that the project is not Categorically Exempt or Statutorically Exempt; therefore, an Initial Study shall be prepared to determine the impacts, level of significance, and appropriate type of environmental document. We have requested that the applicant prepare a preliminary seismic study and Vulnerability Evaluation Framework in order to assist us in determining the impacts relative to induced seismic activity and groundwater quality. Both items remain outstanding.

The following summarizes our concerns regarding the administrative draft permit:

1. The subject site is in close proximity to the Montezuma Fault pursuant to the attached exhibit prepared by the California Division of Mines and Geology, Fault Evaluation Program, 1983. Given the depth of the wells, the injection activity and the proposal to store compressed carbon dioxide, there is potential for induced seismic activity at the subject site. The draft permit does not address such risks or mitigation to reduce such risks.

2. According to the Vulnerability Evaluation Framework (VEF) published by EPA, a qualitative risk assessment should be prepared in accordance with the VEF guidelines. Has a risk assessment been prepared? If so, please provide us a copy.

3. Groundwater testing described on paragraph 3(a) on page 7 of the permit is not clear. For example: 1st paragraph imply only TDS testing of "target injection formation water" but there is no definition of "target injection formation water". It also appears that the sole purpose of groundwater testing is to determine compatibility of the injectate with the injection formation. In addition, monitoring on page 22 appears to monitor only the injection fluids. It does not appear that there are any groundwater testing of the upper aquifers. The subject site is in close proximity to rural residential development namely the community of Collinsville. The upper aquifers are potential drinking water sources, therefore; testing should be accomplished to determine any potential cross contamination or any adverse health effects on the upper aquifers from this project.

4. Casing and Completion Specifications on page 11 cited the cement evaluation and specifications. However, there are no stated construction Quality Assurance requirements. An independent quality assurance contractor should be present during construction and submit reports to Solano County's Department of Resource Management.

5. Mechanical Integrity on page 16 to 21 does not have any requirements for any potential emergency procedure in the event of a loss of operational integrity of the well. Development of an emergency procedure should be developed to increase operational safety.

6. Please include in the EPA UIC permit that the approval of the EPA UIC permit shall be contingent upon approval of Solano County's Land Use Permit. In addition, the project proponent shall comply with the conditions and terms of the Solano County's Use Permit. (Reference No. U-09-13, Assessor's Parcel No. 0090-090-280).

Please advise if you need any further clarification. I may be contacted by email Nnferrario@solanocounty.com or phone (707) 784-3170.

Sincerely,

Nedzlene Ferrario

Nedzlene Ferrario
Senior Planner

Enclosure:
California Division of Mines and Geology, Fault Evaluation Map

C: David Albright, US EPA

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY

DMG OPEN-FILE REPORT 83-10

SUMMARY REPORT: FAULT EVALUATION PROGRAM, 1981-1982 AREA— NORTHERN COAST RANGES REGION, CALIFORNIA

1983

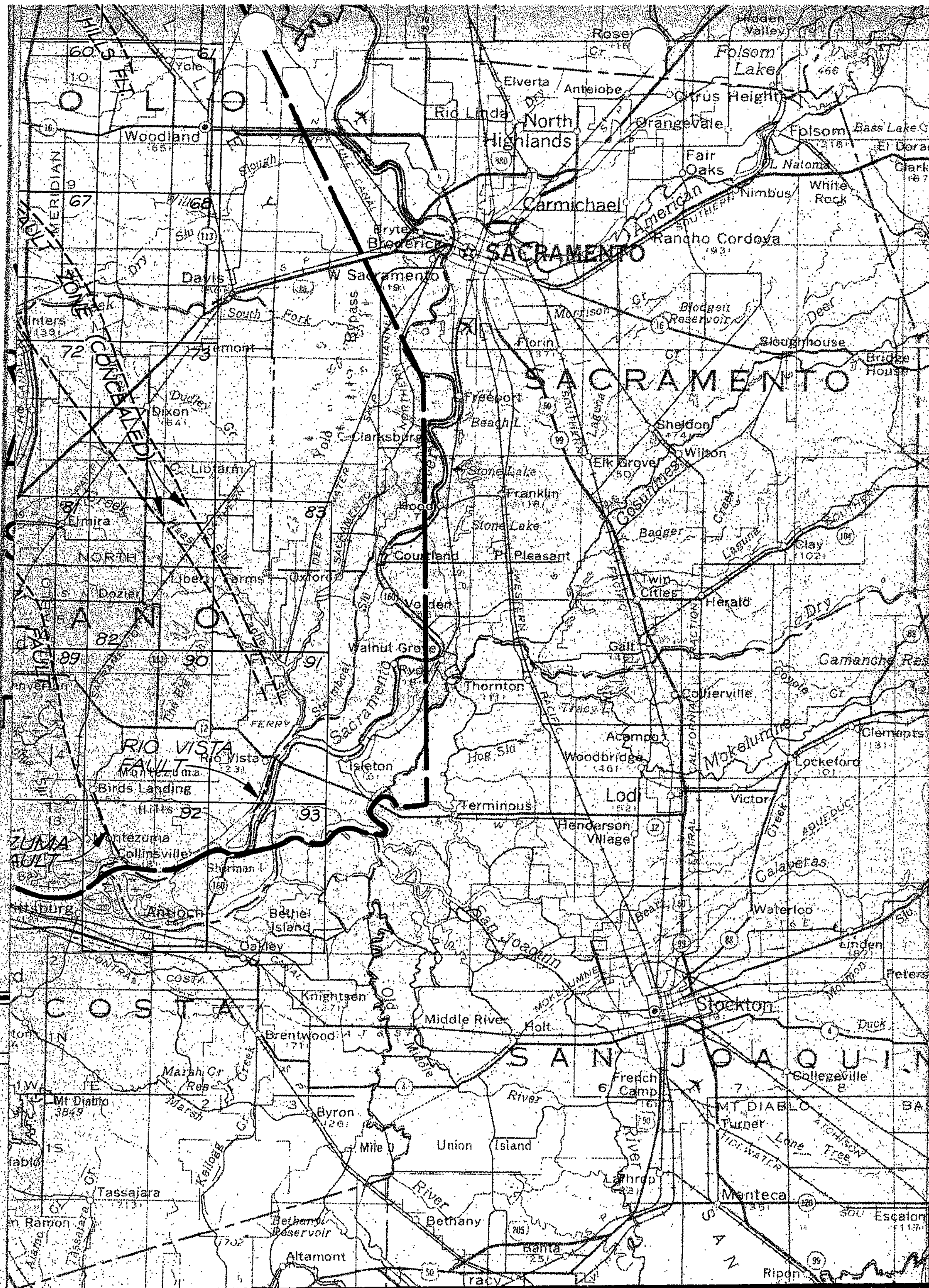
THE RESOURCES AGENCY
GORDON K. VAN VLECK
SECRETARY FOR RESOURCES

STATE OF CALIFORNIA
GEORGE DEUKMEJIAN
GOVERNOR

DEPARTMENT OF CONSERVATION
RANDALL M. WARD
DIRECTOR

Table 1. Summary of faults evaluated during 1981-1982 in the northern Coast Ranges (cont.)

Fault name (alphabetical by counties)	Fault evaluation report (FER) #; investigator	Description of fault (including evidence for recency and inactivity). Is fault well-defined?	Development pressure	Zoning recommendation; comments.
SOLANO COUNTY (cont.)				
2. Green Valley	126; Bryant	Generally well-defined, right-lateral, strike-slip fault with abundant geomorphic evidence of significant Holocene slip; offset fences indicate historic creep and trenches exposed offset soil of probable Holocene age. Northern projection of fault concealed by landslides. Branches mostly not well-defined and lack Holocene evidence of slip.	mod.	New zone recommended for northern segment; revised zone recommended for southern segment.
3. Midland	133; Bryant	Concealed fault that offsets Oligocene strata, but is not known to offset overlying upper Tertiary units. Considered by some as a source of 1892 Vacaville earthquake which produced ground fissures east of Allendale. Although numerous tonal lineaments and several right-laterally deflected drainages exist in Pleistocene alluvium near Allendale, these features could not be clearly associated with faulting and Holocene features were lacking.	low-mod.	Zoning not recommended.
4. Rio Vista	136; Bryant	Well-defined, linear escarpment in Pleistocene deposits inferred to be a fault, but could be erosional; lacks Holocene evidence of faulting.	low	Zoning not recommended.
5. Vaca-Montezuma Hills zone	136; Bryant	Northwest-trending zone of discontinuous, faults and inferred faults based partly on large-scale geomorphic features (linear scarps and hills, deflected drainages) suggestive of Quaternary faulting; however, some of the features may be erosional. Lacks detailed features indicative of Holocene movement. Most segments poorly defined.	low-mod.	Zoning not recommended.



Fault Evaluations by W.A.Bryant, T.C.Smith and E.W.Hart
Drafted by E.Taylor
January 1983

Non-confidential Draft UIC Comments from C6 Resources LLC
Damonica.Pierson to: Michele Dermer 05/25/2010 08:12 AM

Michele, attached below are copies of C6 Resources LLC's comments without the 'confidential' designation. However, I would like to ask that the following statement accompany our comments when shared with other entities:

"The attached comments provided by C6 Resources LLC were made during their technical review of the Draft UIC Permit with the understanding that there would be subsequent discussions to clarify intent and calibrate expectations with EPA. The comments are not meant to be representative of C6 Resources' final position on the permit requirements, but instead serve as a starting point for continued discussion. Any additional use or publication of these comments should be qualified with this statement as it clarifies the context of the statements contained therein."

<<C6 Resources Draft Permit R9UIC-CA5-FY09-1_C6 Resources.ZIP>> <<Draft UIC Comments_C6 Resources_052510.ZIP>>

DaMonica Pierson
Sr. Technical Advisor
Shell Exploration and Production
Upstream Americas CO2/CCS
150 N. Dairy Ashford
Houston, TX 77079

Phone (832) 337-2172
Cell (713) 677-4374
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For further information, please contact the EPA Call Center at
(866) 411-4EPA (4372). The TDD number is (866) 489-4900.

*********************** ATTACHMENT NOT DELIVERED ***********************

*********************** ATTACHMENT NOT DELIVERED *******************

This Email message contained an attachment named
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(866) 411-4EPA (4372). The TDD number is (866) 489-4900.

*********************** ATTACHMENT NOT DELIVERED **********************

C6 Resources' Comments on EPA's Draft UIC Permit--Uncompressed Word Files
Damonica.Pierson
to:
Michele Dermer, David Albright
05/14/2010 12:54 PM
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History: This message has been replied to and forwarded.

Michele, please let me know if the attached .doc files make it through EPA's server.

Michele and David, please find attached a redlined Word version of the Draft UIC Permit that includes our edits and a separate document that chronicles our questions and comments regarding specific sections of the permit. Please let me know if you have any questions or require clarification. Thanks.

<<C6 Resources Draft Permit R9UIC-CA5-FY09-1_C6 Resources.doc>> <<Draft UIC Comments_C6 Resources.doc>>

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Clifford Covey, Interim Director

May 23, 2010

Michele Dermer
Environmental Scientist, Underground Injection Control
U.S. Environmental Protection Agency, Region 9
75 Hawthorne Street (WTR-9)
San Francisco, CA 94105-3901

Re: C6 Resources LLC –Draft US EPA UIC Permit

Dear Michele:

We appreciate the opportunity to review and comment on the Administrative Draft UIC Permit.

The proposal is subject to a discretionary Land Use Permit approval by the Solano County Planning Commission; thus, subject to the California Environmental Quality Act. The Planning Division has determined that the project is not Categorically Exempt or Statutorically Exempt; therefore, an Initial Study shall be prepared to determine the impacts, level of significance, and appropriate type of environmental document. We have requested that the applicant prepare a preliminary seismic study and Vulnerability Evaluation Framework in order to assist us in determining the impacts relative to induced seismic activity and groundwater quality. Both items remain outstanding.

The following summarizes our concerns regarding the administrative draft permit:

1. The subject site is in close proximity to the Montezuma Fault pursuant to the attached exhibit prepared by the California Division of Mines and Geology, Fault Evaluation Program, 1983. Given the depth of the wells, the injection activity and the proposal to store compressed carbon dioxide, there is potential for induced seismic activity at the subject site. The draft permit does not address such risks or mitigation to reduce such risks.

2. According to the Vulnerability Evaluation Framework (VEF) published by EPA, a qualitative risk assessment should be prepared in accordance with the VEF guidelines. Has a risk assessment been prepared? If so, please provide us a copy.

3. Groundwater testing described on paragraph 3(a) on page 7 of the permit is not clear. For example: 1st paragraph imply only TDS testing of "target injection formation water" but there is no definition of "target injection formation water". It also appears that the sole purpose of groundwater testing is to determine compatibility of the injectate with the injection formation. In addition, monitoring on page 22 appears to monitor only the injection fluids. It does not appear that there are any groundwater testing of the upper aquifers. The subject site is in close proximity to rural residential development namely the community of Collinsville. The upper aquifers are potential drinking water sources, therefore; testing should be accomplished to determine any potential cross contamination or any adverse health effects on the upper aquifers from this project.

4. Casing and Completion Specifications on page 11 cited the cement evaluation and specifications. However, there are no stated construction Quality Assurance requirements. An independent quality assurance contractor should be present during construction and submit reports to Solano County's Department of Resource Management.

5. Mechanical Integrity on page 16 to 21 does not have any requirements for any potential emergency procedure in the event of a loss of operational integrity of the well. Development of an emergency procedure should be developed to increase operational safety.

6. Please include in the EPA UIC permit that the approval of the EPA UIC permit shall be contingent upon approval of Solano County's Land Use Permit. In addition, the project proponent shall comply with the conditions and terms of the Solano County's Use Permit. (Reference No. U-09-13, Assessor's Parcel No. 0090-090-280).

Please advise if you need any further clarification. I may be contacted by email Nnferrario@solanocounty.com or phone (707) 784-3170.

Sincerely,

Nedzlene Ferrario
Senior Planner

Enclosure:
California Division of Mines and Geology, Fault Evaluation Map

C: David Albright, US EPA

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY

DMG OPEN-FILE REPORT 83-10

SUMMARY REPORT: FAULT EVALUATION PROGRAM, 1981-1982 AREA— NORTHERN COAST RANGES REGION, CALIFORNIA

1983

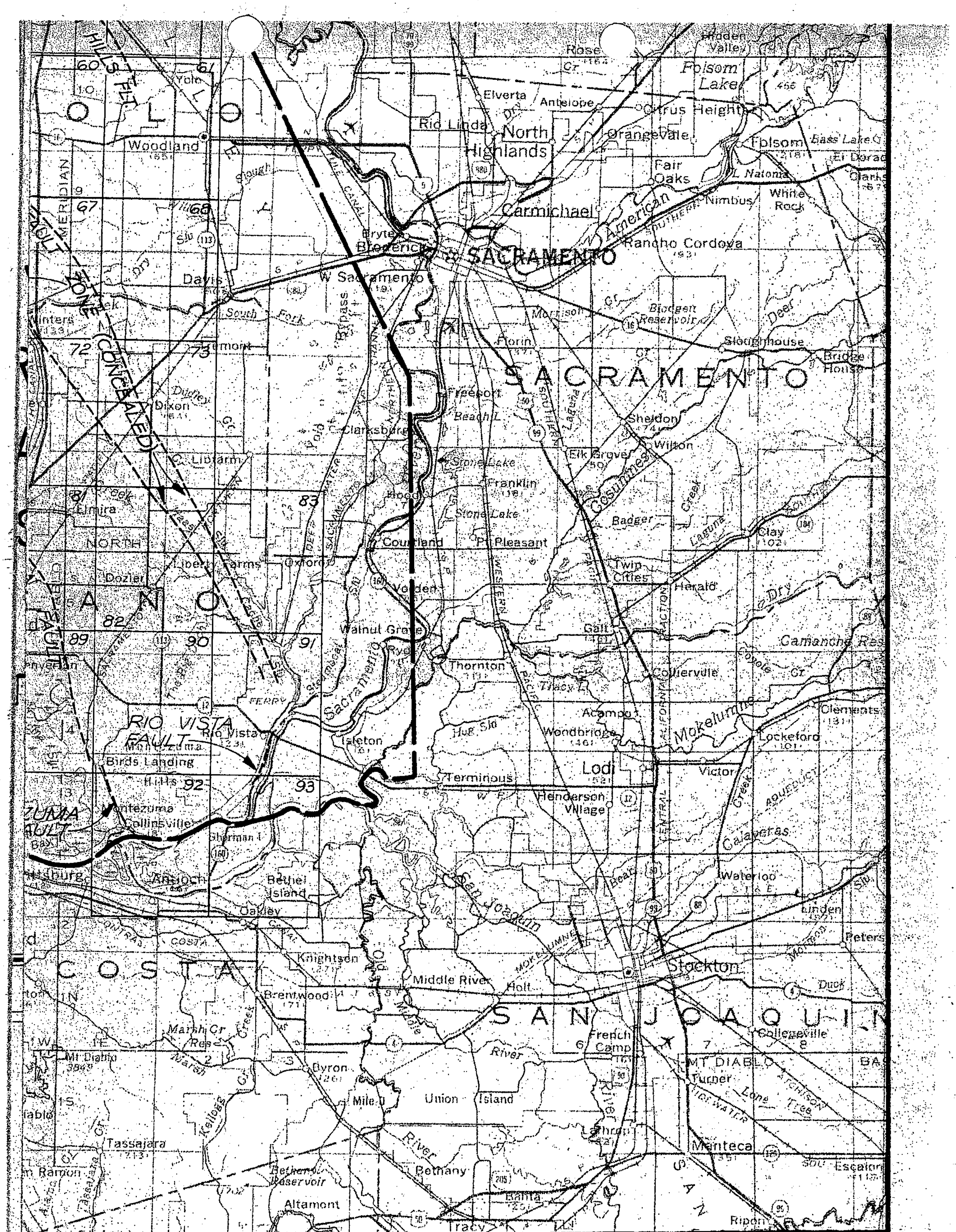
THE RESOURCES AGENCY
GORDON K. VAN VLECK
SECRETARY FOR RESOURCES

STATE OF CALIFORNIA
GEORGE DEUKMEJIAN
GOVERNOR

DEPARTMENT OF CONSERVATION
RANDALL M. WARD
DIRECTOR

Table 1. Summary of faults evaluated during 1981-1982 in the northern Coast Ranges (cont.)

Fault name (alphabetical by counties)	Fault evaluation report (FER) #; investigator	Description of fault (including evidence for recency and inactivity). Is fault well-defined?	Development pressure	Zoning recommendation; comments.
SOLANO COUNTY (cont.)				
2. Green Valley	126; Bryant	Generally well-defined, right-lateral, strike-slip fault with abundant geomorphic evidence of significant Holocene slip; offset fences indicate historic creep and trenches exposed offset soil of probable Holocene age. Northern projection of fault concealed by landslides. Branches mostly not well-defined and lack Holocene evidence of slip.	mod.	New zone recommended for northern segment; revised zone recommended for southern segment.
3. Midland	133; Bryant	Concealed fault that offsets Oligocene strata, but is not known to offset overlying upper Tertiary units. Considered by some as a source of 1892 Vacaville earthquake which produced ground fissures east of Allendale. Although numerous tonal lineaments and several right-laterally deflected drainages exist in Pleistocene alluvium near Allendale, these features could not be clearly associated with faulting and Holocene features were lacking.	low-mod.	Zoning not recommended.
4. Rio Vista	136; Bryant	Well-defined, linear escarpment in Pleistocene deposits inferred to be a fault, but could be erosional; lacks Holocene evidence of faulting.	low	Zoning not recommended.
5. Vaca-Montezuma Hills zone	136; Bryant	Northwest-trending zone of discontinuous, faults and inferred faults based partly on large-scale geomorphic features (linear scarps and hills, deflected drainages) suggestive of Quaternary faulting; however, some of the features may be erosional. Lacks detailed features indicative of Holocene movement. Most segments poorly defined.	low-mod.	Zoning not recommended.



Fault Evaluations by W.A.Bryant, T.C.Smith and E.W.Hart
Drafted by E.Taylor
January 1983